THE HYDROGEOLOGY OF
THE DIAMOND HARBOUR REGION,
BANKS PENINSULA

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A thesis
submitted in partial fulfilment
of the requirements for the degree
of
Master of Science in Engineering Geology,
University of Canterbury.

By
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ERRATA

Page 181, Lines 2 and 3 "approximately 100 m^3/minute" should read 1 m^3/minute

Page 193, Line 33 "around 144,000 m^3/day" should read around 1,440 m^3/day

Page 194, Lines 1 to 3 "the local water resources can only be expected to provide a small contribution to the daily needs of the township" should read the total local water resources can be expected to provide a contribution of between 40 and 90 percent of the daily needs of the township

Page 201, Insert as last sentence The total available water resources could therefore provide between 40 and 90 percent of the requirements of the Diamond Harbour Township.

ABSTRACT

The study area comprises an area of about 40 km^2 and includes the township of Diamond Harbour located on the sourthern side of Lyttelton Harbour. The area is broken up into two valley systems (Orton Bradley and Purau Valleys) separated by a gently northward dipping slope known as the Diamond Harbour 'Dip-slope'. Pressure on a water reticulation pipeline due for repair or replacement, combined with an increasing population, formed the basis for this investigation. It was hoped that local groundwater resources could at least supplement the domestic supply coming from Lyttelton.

Drill hole and geophysical information confirmed that the sediments that fill the lower Purau and Orton Bradley Valleys consist of river clays and silts, marine/estuarine muds and a number of gravel units. In the case of the Purau Valley two aquifers were located, a first probably representing an infilled river channel or channels immediately overlying volcanic bedrock (Lower Purau Aquifer), and a second river gravel unit which is saturated only within 200m of the coast (Upper Purau Aquifer). While no borehold data was available to confirm geophysical data interpretations for the Orton Bradley Valley, the indications are that a single river gravel unit exists, and that it is saturated near the coast.

Pump test results for the Lower Purau Aquifer show that this aquifer has a transmissivity of 11.92m^2/day and a storage coefficient of 3.87×10^{-4}. Computer modelling indicated the Lower Purau Aquifer possesses two hydraulic boundaries 14 and 50m from the pumped bore, and this is consistent with the interpretation of the aquifer being an infilled river channel of approximately 64m width.

Evidence suggests that the alluvial aquifers of both valleys are recharged from deep circulating groundwaters present in fractured bedrock aquifers located within the

volcanic formations found in the area. Isotope and chemical evidence suggests that the alluvial and deep circulating groundwaters are similar in their relative concentrations of most ions, and have similar residence times of about 50 years. The deep and alluvial groundwaters are fit for domestic supply provided treatment is carried out for excessive concentrations of iron and manganese, and aeration to bring low pH values to within acceptable limits.

An experiment on a known perennial High Altitude Spring indicates that the increased discharge seen following a rain event is composed almost entirely of 'old' stored water, and the increased flow is due to increased pressure head following recharge of the aquifer system by meteoric waters. Superimposed on this event variability is a seasonal discharge variability related to seasonal rainfall patterns. An infiltration-'head'/storage model is proposed to explain the behaviour of the High Altitude Springs of Diamond Harbour. Isotopic evidence suggests an exponential-piston flow model is consistent with observed results and this indicates the spring groundwaters have residence times of 10 to 25 years.

An estimate of the safe yield from all available water resources in the Diamond Harbour area ranges from 660 to $1300 m^3$/day, allowing for sufficient water to maintain acceptable river baseflows.

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APPENDICES

ACKNOWLEDGEMENTS

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Lastly, I am grateful to my wife Jeanette who has endured much to see this thesis through, and who has typed her fingers to the bone in the process.

CHAPTER ONE

INTRODUCTION

1.1 PROJECT BACKGROUND

The study area comprises an area of approximately 40 km^2 located on the southern side of Lyttelton Harbour, Banks Peninsula (Fig. 1.1). It incorporates two large valley systems running approximately north - south, each separated from the other by a long, gently northward dipping slope, known as the "Diamond Harbour Dip-slope". The western valley is referred to as the Orton Bradley valley, and the eastern valley as the Purau valley. While the Diamond Harbour village represents the largest built up area, holiday houses and permanent residences are scattered along the coast.

The study was conducted on behalf of the Lyttelton Borough Council as an investigation into potential groundwater resources in the area, and it also formed part of a larger investigation into the groundwater resources of Banks Peninsula presently being conducted by the North Canterbury Catchment Board (NCCB). The principal objective of this study was to assess and delineate the groundwater system in the Diamond Harbour area, particularly the Orton Bradley and Purau valleys, so that adequate geological models could be produced to assist in developing appropriate management strategies. Also it was hoped the study would be able to quantify the available resource in the area.

Diamond Harbour township is supplied via a submarine pipeline from Lyttelton. Currently this pipeline is due for either upgrading or replacement. As new residential subdivisions are opened up increasing pressure will be placed on this pipeline to supply a larger population. This study was commissioned with regard to determining the potential of the groundwater resource in the area to meet at least some of this need. Other options open to the Lyttelton

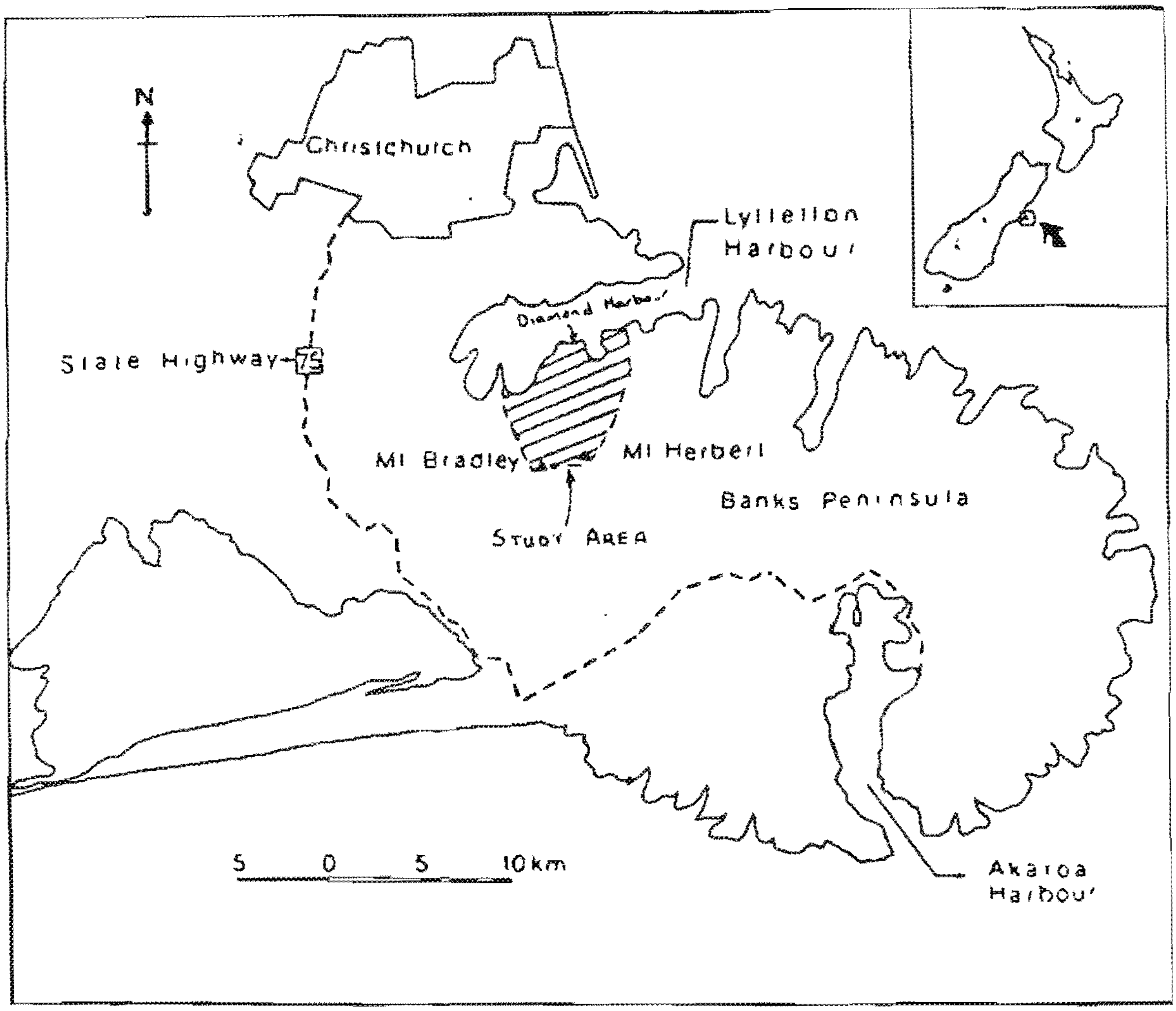


Fig. 1.1 Location Map

Borough Council include use of the surface water resource in the area, and plans for a dam to be located in the lower Purau valley were infact drawn up in the 1930's as part of a feasibility study.

1.2 THESIS STUDY METHODS

The investigation included the following study techniques:

1) Engineering and hydrogeological mapping of the Diamond Harbour area in order to determine site development history and geological controls on groundwater occurrence and movement.

2) Engineering geophysical investigations, principally seismic refraction and resistivity surveys, to supplement field geological information and to determine the extent of any alluvial and bedrock aquifers.

3) Spring discharge monitoring of selected springs for a one year period to determine seasonal variation.

4) Continual flow recording of a selected spring over a period of approximately one month, including rainfall monitoring, to determine spring response to rainfall.

5) Meteorological studies to determine precipitation trends and provide data for water balance calculations.

6) River discharge monitoring over a period of one year to obtain surface water movement trends for the Purau river and to determine any groundwater recharge from this source.

7) Isotopic studies of spring and valley floor aquifer waters to determine residence times and recharge sources.

8) Chemical testing of selected springs, bores and/or streams to determine water quality and to assist in sourcing waters.

1.3 CLIMATE

1.3.1 Introduction

Precipitation patterns are the key in determining whether groundwater resources can offer dependable long term supplies of water. Although potential aquifers may exist in the Diamond Harbour area it will be climatic factors that will determine how much recharge they will receive and hence, their usefulness as a water resource.

The climate of Banks Peninsula is largely influenced by the following factors:

1) The presence of the Southern Alps some 65 km to the west.

2) Its isolated position as a volcanic promontory in the pathway of seasonal wind patterns.

3) Its sharp variations in relief and the presence of many deeply incised valleys, and

4) The presence of the sea surrounding most of the Peninsula.

1.3.2 Prevailing Winds

The prevailing wind directions are east-northeasterly and from the southwesterly quarter. Other wind directions are noticeably less frequent (Fig. 1.2 from McGann, 1983).

Seasonally there is a marked variation in wind patterns. Westerly winds have a distinct winter minimum and dominate in October and to a lesser extent in early autumn. Southerlies dominate in late autumn and early winter, with a distinct minimum in March and August when northerlies clearly dominate. Easterly winds have a clear maximum in winter and a marked reduction in spring as westerlies increase (Fig. 1.3a-d).

1.3.3 Precipitation Patterns

While the predominant wind directions for the Canterbury Plains are east-northeast and southwest, 75% of the mean annual rainfall occurs with winds between south and west. Banks Peninsula's situation is slightly more complex. Sturman (1986) has shown that cyclonicity correlates highly with monthly precipitation over and around Banks Peninsula, and that precipitation over the Peninsula is more highly correlated with easterly airflow than southerly (Fig. 1.4). Cyclonic circulation has a maximum frequency in winter and a minimum in summer.

Figure 1.5 shows the average annual rainfall over the study area. From this and Table 1.1 it can be seen that Banks Peninsula has a wetter climate than the surrounding Canterbury Plains and reflects the Peninsula's influence as a "rain catcher"(Trewinard et. al.,1986). Generally, the Peninsula's precipitation is orographic in origin and hence there are obvious altitudinal effects on rainfall distribution. Mount Herbert, in the study area, represents one of three sites on the Peninsula where annual rainfall is usually above 1000mm (Jayet, 1986).

The presence of deeply incised valleys means that rainbearing winds can penetrate far into the Peninsula before being forced to rise at the head of each valley. A consequence of this is that rainfall tends to be higher at the heads of most valleys (Fig. 1.5).

While there is some variation on the Peninsula it is generally true that precipitation reaches a maximum during

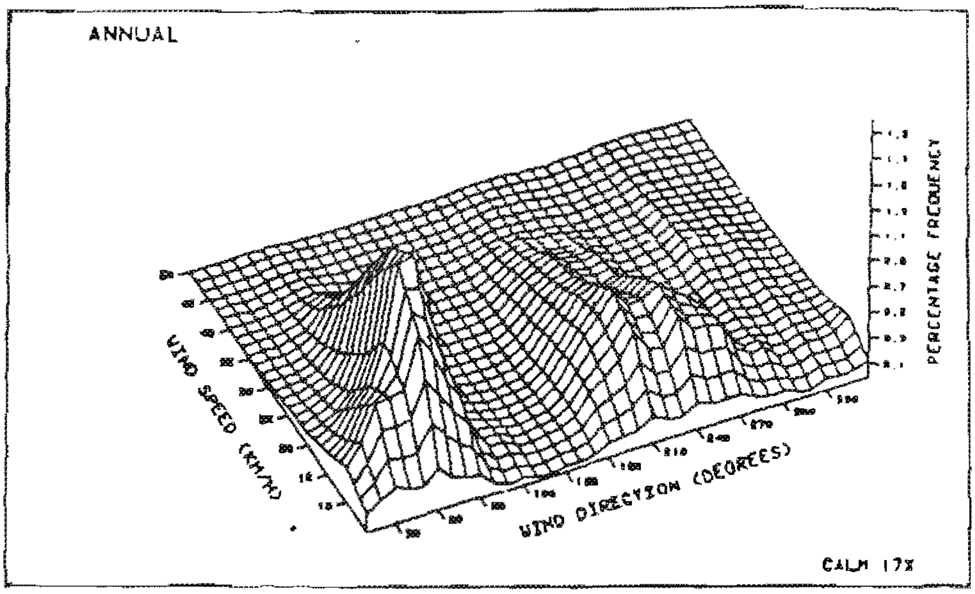


Fig. 1.2 Annual percentage frequency of occurrence of winds at Christchurch Airport. (From McGann, 1983)

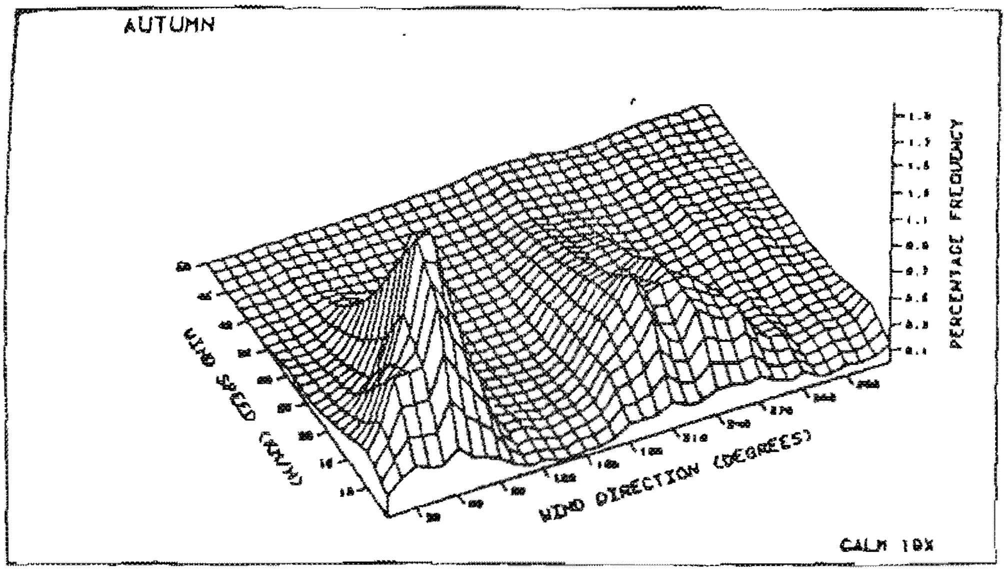


Fig. 1.3a Percentage frequency of occurrence of winds in autumn at Christchurch Airport. (From McGann, 1983)

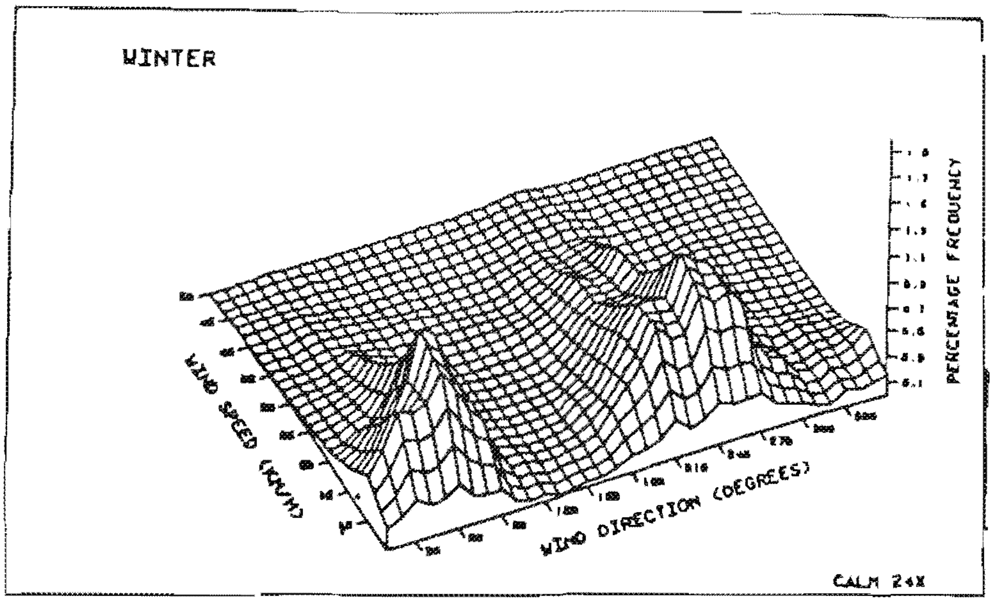


Fig. 1.3b Percentage frequency of occurrence of winds in winter at Christchurch Airport. (From McGann, 1983)

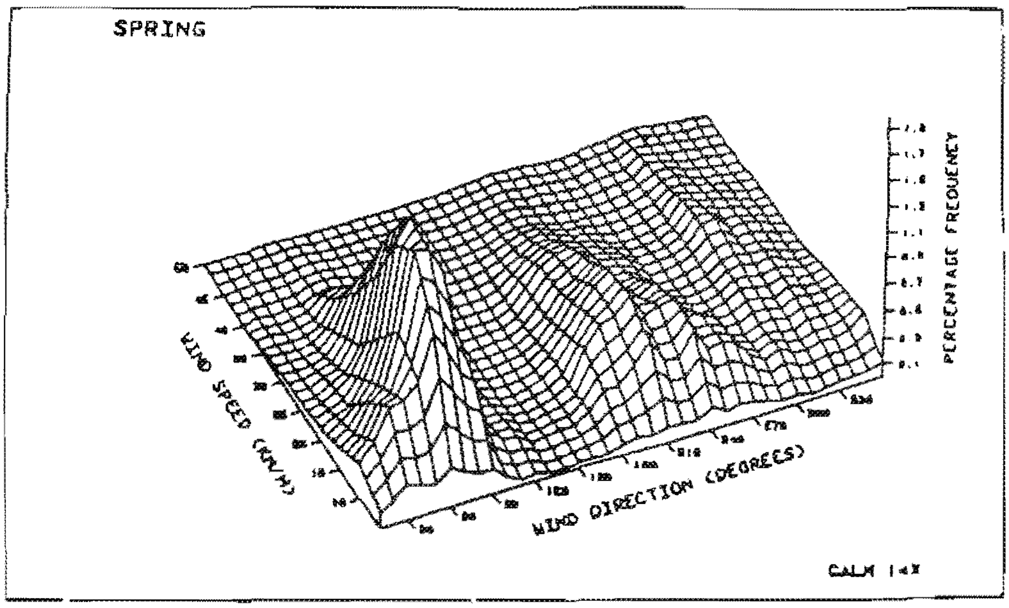


Fig. 1.3c Percentage frequency of occurrence of winds in spring at Christchurch Airport. (From McGann, 1983)

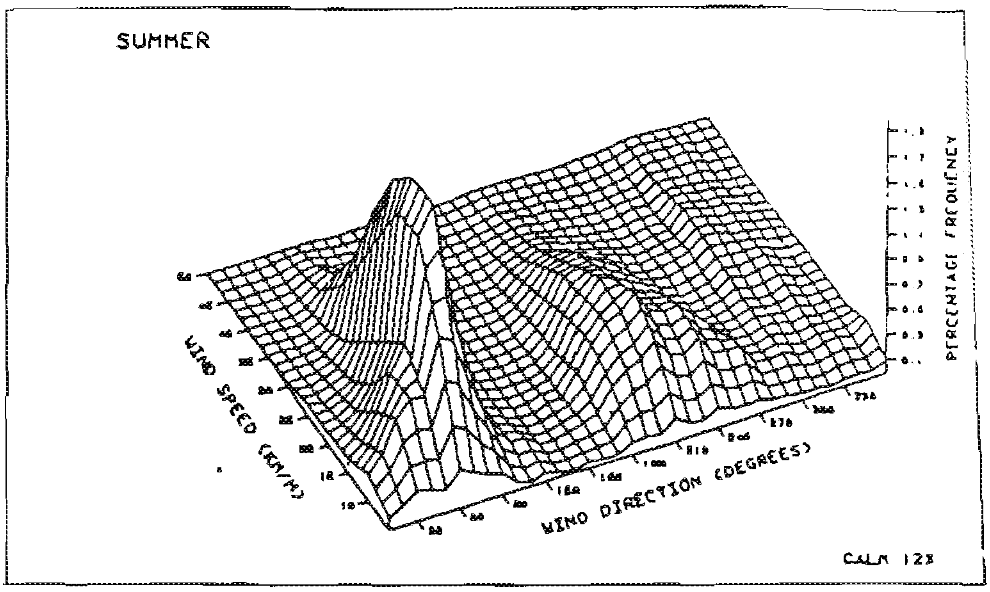


Fig. 1.3d Percentage frequency of occurrence of winds in summer at Christchurch Airport. (From McGann, 1983)

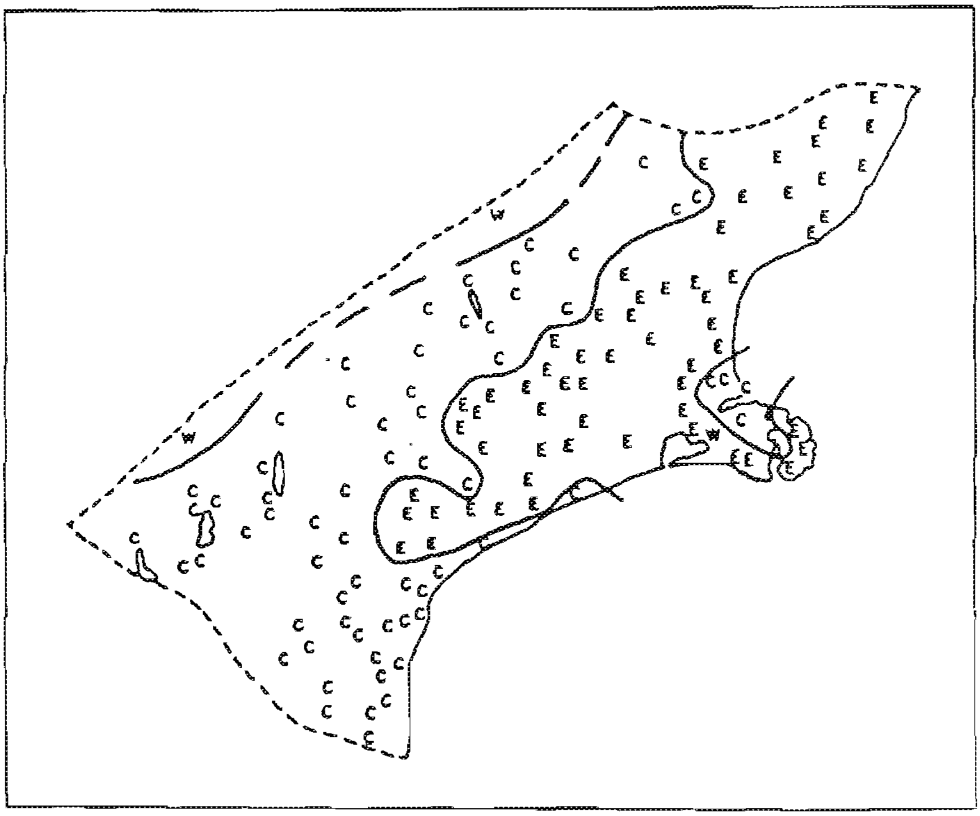


Fig 1.4 Spatial distribution of the most important monthly precipitation predictor based on stepwise multiple regression. C=Cyclonicity, W=Westerly, E=Easterly. (From Sturman, 1986)

the winter months and a minimum during the summer period (Table 1.1). Jayet (1986) comments that some of the Peninsula's wettest rainfall stations receive as much (or more) rainfall in the winter months as some of the drier stations get in an average year. This fact is important when considering the location and behaviour of high altitude springs on the Peninsula.

Precipitation falls mainly as rain, but snowfalls are not uncommon at high altitude during the winter months. Mist and fog also produce precipitation in high altitude areas and valley heads during the winter months.

1.3.4 Temperature

Jayet (1986) has found that Peninsula temperatures are on average higher that those of the Canterbury Plains, with less extreme maxima and minima. Peninsula minimum temperatures are higher than those on the Plains due to the moderating influence of the sea and a lesser influence of the cold airflow from the Southern Alps.

1.4 VEGETATION AND LANDUSE

It has been estimated that in 1860 native forests covered about 46945 hectares or approximately 47% of Banks Peninsula (Petrie, 1963). Since the later part of the nineteenth century most of these forests have been removed, and in their place are tussock and hand sown grasslands. Today, surviving remnants or pockets of secondary growth are confined to shady slopes and valley heads. The presence of rushes and flax bushes has often been found useful in locating perennial springs in the study area.

Farming is almost entirely pastoral with sheep and beef production forming the basis of the regions economy for the past 35 years. Prior to 1950 dairying and Cocksfoot grass grown for seed were the dominant forms of farming. More recently sheep numbers have increased and dairying has gone

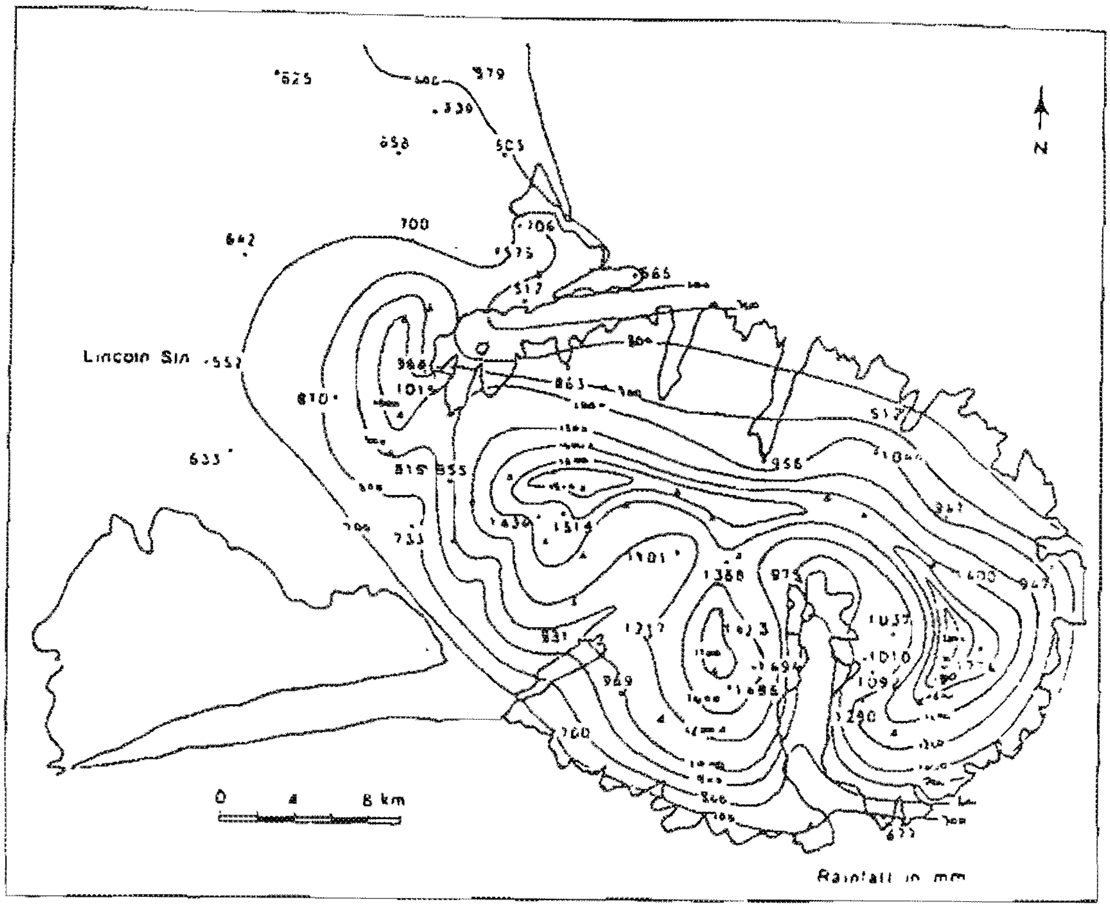


Fig. 1.5 Mean annual rainfall in the Banks Peninsula (based on rainfall data from a period of 1950 to 1985) (From Jayet, 1986)

Table 1.1 Rainfall Data - Diamond Harbour

Month	Christchurch Airport (mm)	Mt Herbert GR 888243 (mm)	Blakley Farm GR 901293 (mm)	Keenan Farm Gr 890302 (mm)
June 1987	88.5	95	51	37.5
July 1987	38.5	118	26	26
August 1987	20.7	70	13	13
September 1987	13.1	33	16	16
October 1987	63.9	70.5	69	69
November 1987	36.2	51.5	29.5	29.5
December 1987	35.9	73.5	32	32
January 1988	17.4	39.5	23	23
February 1988	40.0	86	20.5	20.5
March 1988	21.7	70	18	18
April 1988	16.9	30	20	20
May 1988	42.5	59	39	39
June 1988	29.8	92.5	49	49
July 1988	30.5	97	30	30
	[illegible]	[illegible]	[illegible]	[illegible]

into decline. Goat farming has also been introduced on a small scale.

Tree planting on a woodlot scale rather than extensive forestry has increased as an alternative landuse. Small scale horticulture has also developed in the area. Much of the shoreline areas have been subdivided to provide for holiday accommodation and recreational land use is on the increase. This will put further pressure on the already limited water resources.

1.5 WATER SUPPLY

Those residents that are not on the municipal supply in Diamond Harbour mostly rely on rainfall for their water supply. This is clearly an unsatisfactory option since even a short dry season will leave most residents without water. Some residents are fortunate enough to have local spring sources or river water as an alternative. Neither of these options are satisfactory because 1) Spring water often has to be piped long distances and stock contamination is always a problem; and 2) River water is subject to discolouration during periods of high flow, making this an unsuitable source for domestic use. During the summer of 1988 daily flow for the Purau river averaged about 1900m^3/day over a particularly dry summer.

Currently irrigation from the Purau river is used to maintain pastures and provide water for small horticultural plots in Purau valley during the summer months. The Purau Motor Camp also has a water right to remove 100m^3/day from the Purau river. During dry summer periods these practices may need to be closely monitored if river baseflows are not to be reduced to unacceptable levels.

There are a number of residents, especially in Purau valley, who have shallow wells that tap a small confined aquifer. This study has shown the aquifer can supply limited (less than 30 m^3/day from the Purau Motor Camp well) quantites of water for domestic use. However, like the Purau river this alluvial aquifer is recharged from volcanic aquifers that relie on local rainfall for their own recharge. Any change in rainfall patterns (due to the Greenhouse effect) will directly influence the amount of water available for use.

1.6 THESIS ORGANISATION

This thesis is organised into six chapters. The first chapter is an introductory chapter outlining the purpose of the study and some basic considerations. The second chapter is a summary of the geological features of the area, and includes a summary of the recent work of Yetton (1983), Sanders (1986), and Namjou (1988) involving research into Banks Peninsula's groundwater resources.

Chapter Three is concerned with the investigation into groundwater found in the alluvial sediments of the Purau and Orton Bradley valleys, and examines the relationship between this groundwater and the deep groundwater found in the area. Chapter Four summarises the results of an investigation of the High Altitude Springs found in Diamond Harbour, in particular the detailed study of one perennial volcanic bedrock spring in the upper Purau valley.

Chapter Five produces a model that attempts to explain the relationship between spring waters and the alluvial groundwaters found in the area, and briefly examines management strategies. Chapter six summarises the conclusions of the study.

1.7 ASSISTANCE

Technical support was gained from members of the DSIR groundwater research team for the geophysical investigation, and DSIR computer programmes were used to process geophysical data. Staff of the NCCB assisted with the the

pump test and processing of pump test data. Processing of stream and spring flow data was also carried out with the assistance of NCCB staff. Water chemistry analysis was carried out by DSIR Chemistry Division, Ilam. All isotope analyses were undertaken by the Institute of Nuclear Sciences, DSIR, Lower Hutt.

Funding for the project was provided by the Lyttelton Borough Council and NCCB. Funding for many of the isotopic analyses used in this study was provided by the Institute of Nuclear Sciences, DSIR, Lower Hutt.

CHAPTER TWO

GEOLOGY AND GROUNDWATER OCCURRENCE

2.1 INTRODUCTION

Banks Peninsula represents a large accumulation of now dissected Miocene volcanic rocks that developed on continental crust at the western end of the Chatham Rise, a bathymetric structural high extending 900 km to the east of Banks Peninsula. (See Table 2.1 for a detailed description of volcanic lithologies found in the study area). While originally an island, the Peninsula has been connected to the mainland by prograding glacial outwash gravels during the late Pleistocene. Also during the Pleistocene there was widespread production of silt-sized material by glacial grinding and periglacial activity. Large volumes of this fine grained material (loess) has been entrained and transported by strong northwesterly winds, with deposition as an airfall blanket over much of Banks Peninsula.

Chapter Two presents a discussion of the volcanic geological history and geomorphic development of Diamond Harbour, based on the work of previous writers. A general discussion of the occurrence of groundwater on Banks Peninsula is also presented here.

2.2 BEDROCK GEOLOGY

2.2.1 Introduction

A number of authors have investigated the geology of central Banks Peninsula over the last 100 years, for example Speight, (1933), Ligget and Gregg, (1965), Stipp and McDougall, (1968), Price and Taylor, (1980), Dorsey, (1981), and Weaver et. al., (1985). The most recent and comprehensive study however, has been that of Sewell, (1985). Sewell also gives a summary of the development in geological thought on the origin of the volcanic products in the study area and the following is a summary based largely on his work.

2.2.2 Geological Evolution

a) Pre-Lyttelton Rocks

The oldest rocks exposed in the study area are found in the lower part of the Orton Bradley valley which forms the western limit to the study area, (Fig. 2.1). The pre-Lyttelton rocks exposed here include early-middle Tertiary sandstone (Charteris Bay Sandstone) and early Miocene Governors Bay volcanics (Gebbies Rhyolite), (Fig. 2.1 and table 2.1)

b) Lyttelton Volcanic Group

The earliest lavas of the Lyttelton volcano were erupted onto an older erosion surface approximately 11-9.7 Ma ago Sewell, (1985), (Fig. 2.1 and Table 2.1). Hawaiian-type eruptions produced thick, extensive hawaiite lava flows with occasional small scoria cones indicating strombolian type activity. During the latter period of activity a large breach occurred in the southeastern crater wall, resulting in the deposition of thick conglomerate and agglomerate now present in the Upper Purau valley.

c) Mt Herbert Volcanic Group

The oldest Mt Herbert lavas (Kaituna Valley Hawaiite) were erupted between c. 9.7 and 9.5 Ma, on the southern flanks of the Lyttelton volcano in the Kaituna valley and also in Port Levy, (Fig. 2.1 and table 2.1) . These lavas are not represented in the study area. A new centre of eruption within Lyttelton volcano developed between c. 9.5 and 8.6 Ma ago to erupt the lower most lavas of the Orton

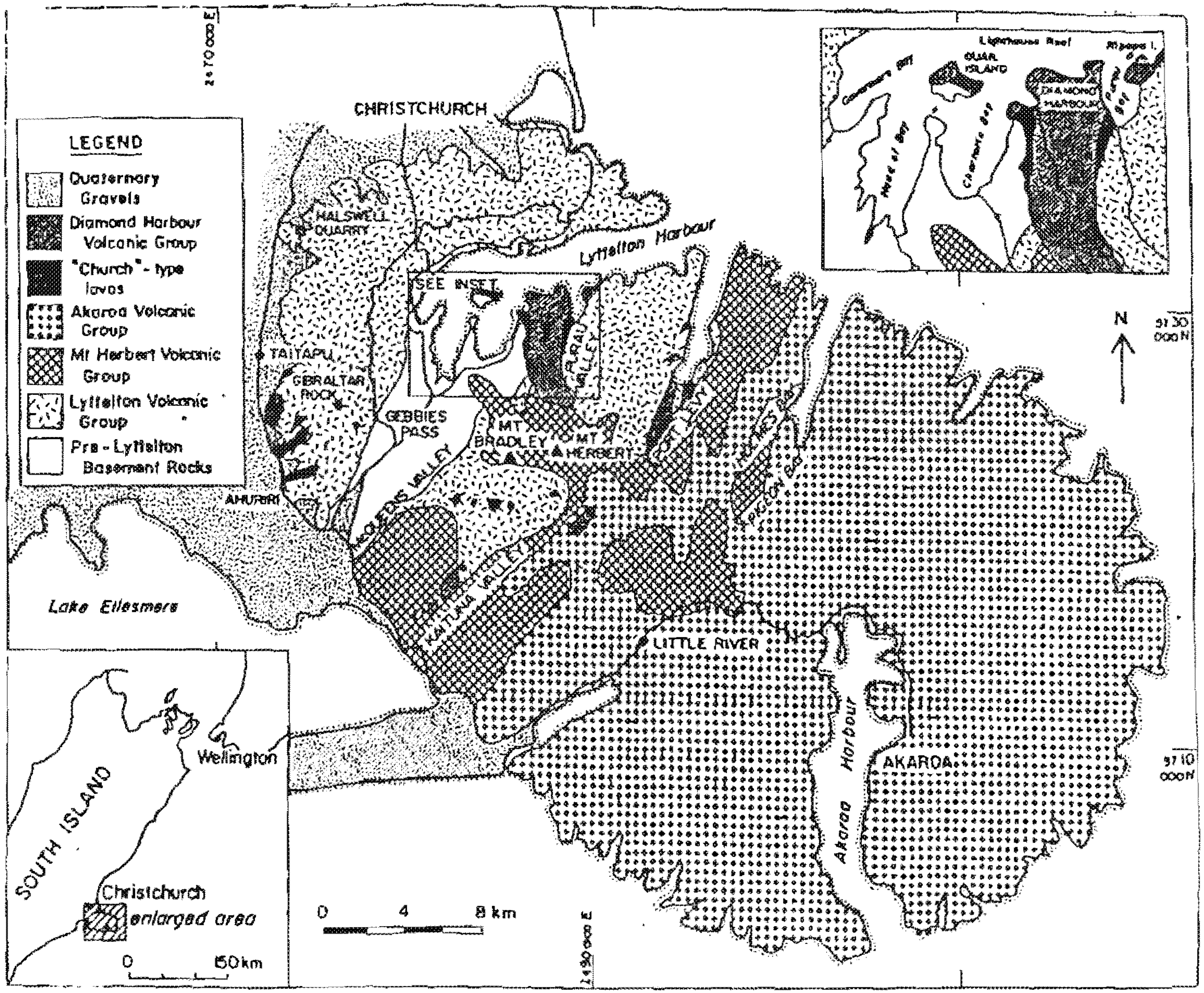


Fig. 2.1 Geological map of Banks Peninsula. (From Weaver et al, 1985)

Table 2.1 STRATIGRAPHY OF MIOCENE VOLCANICS OF BANKS PENINSULA
(From Sewell, 1985)

GROUP	ESTIMATED VOLUME	FORMATION	K/Ar AGE RANGE (Ma)	LITHOLOGY	MAIN LOCALITIES	STRATIGRAPHIC RELATIONSHIPS
DIAMOND HARBOUR VOLCANIC GROUP	20 km³	STODDART BASALT	7·0 - 5·8	Fresh, columnar-jointed, olivine ± clinopyroxene phyric basanites, olivine-basalts and olivine-hawaiites – rare olivine-basalt dikes	Tallapu - Ahuriri, Kaituna Valley Port Levy, Diamond Harbour, Quail Island	STODDART KAIORURU HAWAIITE
		KAIORURU HAWAIITE	6·9 - 6·8	Commonly weathered, vesicular, pale pink, olivine + clinopyroxene-phyric and aphyric olivine-hawaiites	Diamond Harbour, Quail Island	BASALT
CHURCH TYPE LAVAS	5 km³	CHURCH BASALT	8·0 - 7·3	Fresh, columnar-jointed, olivine ± clinopyroxene ± plagioclase-phyric olivine-basalts	Diamond Harbour, Quail Island, Tallapu - Ahuriri	CHURCH
		CHATEAU INTRUSIVES	8·0	Grey, columnar to knobbly-jointed aphyric hawaiites	Charteris Bay - Bradley Park	DARRA BASALT
		DARRA BASANITOID	8·1 - 7·7	Fresh, columnar-jointed olivine ± clinopyroxene-phyric basanitoids -rare basanitoid dikes	Diamond Harbour, Quail Island, Ahuriri - Tallapu	BASANITOID
AKAROA VOLCANIC GROUP	1200 km³		9·0 - 8·0	Fresh, medium to fine-grained, olivine-clinopyroxene-plagioclase-phyric and grey, aphyric hawaiites - rare trachyte domes and dikes	South side of Kaituna Valley - Port Levy	MT HERBERT HAWAIITE AKAROA VOLCANIC GROUP
MT HERBERT VOLCANIC GROUP	100 km³	MT HERBERT HAWAIITE	8·5 - 8·0	Grey, columnar-jointed, aphyric and rarely olivine-phyric olivine-hawaiites	Mt Herbert - Mt Bradley	ORTON BRADLEY PORT
		PORT LEVY FORMATION	8·9 - 8·5	Grey-black, columnar-jointed, aphyric hawaiites-rare porphyritic basalts and mugearites	Port Levy - Western Valley	FORMATION LEVY
		ORTON - BRADLEY FORMATION	9·5 - 8·6	Black, fresh aphyric, olivine-hawaiites & olivine + clinopyroxene ± plagioclase-phyric olivine-basalts	Mt Herbert - Mt Bradley	FORMATION
		KAITUNA HAWAIITE	9·7 - 9·5	Columnar-jointed, dark grey-black, fresh, olivine + clinopyroxene-phyric olivine-hawaiites	Kaituna - McQueens Valleys	KAITUNA HAWAIITE
LYTTELTON VOLCANIC GROUP	450 km³		11 - 10	Moderately weathered, plagioclase ± olivine ± clinopyroxene-phyric hawaiites -trachyte lava flows and domes -numerous trachytic and basaltic dikes	North side of Kaituna Valley - Mt Herbert	LYTTELTON VOLCANIC GROUP

Bradley Formation. These consist principally of hawaiites and minor olivine basalts.

The development of a freshwater lake on the floor of the Lyttelton crater between 9.3 and 9.1 Ma led to the deposition of fragmental and largely juvenile breccia, which was mostly derived from a tuff cone to the northwest, and is mapped as the Mt Bradley Volcaniclastic Member (Fig. 2.1 and Table 2.1).

A renewed phase of volcanism with a centre in the vicinity of Mt Herbert produced hawaiite lavas that dip northwards over the mudstones that cap the volcaniclastic lake sediments. A tuff Cone building phase, followed by renewed eruption of hawaiite lavas from the main vent, closed the breach in the Lyttelton crater wall.

From 8.9 to 8.5 Ma the main focus of activity occurred in the Port Levy area and resulted in the eruption of the Port Levy Formation which is not represented in the study area. A final phase of activity resulted in the eruption of the youngest of the Mt Herbert lavas, the Herbert Peak Hawaiite, from 8.5 to 8.0 Ma, (Fig. 2.1 and Table 2.1).

d) 'Church Type' Lavas

From about 8 Ma eruption of Church type lavas occurred within the Lyttelton crater, (Fig. 2.1 and Table 2.1). The Darra Basanitoid was probably erupted during the final phase of Mt Herbert and Akaroa Volcanism, 8.1-7.7 Ma. The Chateau Intrusives were probably also emplaced at this time (8.0 Ma), and consist of aphyric hawaiites. Church Basalts consisting of phyric olivine basalts were erupted between 8.0 and 7.3 Ma. Some of these minor geological units are present in the study area, (Fig. 2.1 and Table 2.1).

e) Diamond Harbour Volcanic Group

Between 7.0 and 6.1 Ma Hawaiian-type eruptions of Stoddart Basalt were characterised by the extrusion of basanite and olivine basalt lavas, with little pyroclastic material, onto the southern flanks of Lyttelton crater (Fig. 2.1 and Table 2.1). From 6.1 to 5.8 Ma the eruption of mainly olivine hawaiite lavas occurred within the crater. Kaioruru lavas were also erupted during this last phase of volcanism.

2.3 GEOMORPHIC DEVELOPMENT

The study area comprises three catchments totalling approximately 40 square kilometres. The Purau catchment of approximately 17 square kilometres, the Orton Bradley catchment of approximately 15 square kilometres and the Dip-slope catchment of approximately 8 square kilometres (Fig. 2.2).

The two valley systems rise from sea level to around 900m a.s.l. in only 5 to 6 kilometres. The valley heads are typically steep and rugged, being separated from the neighbouring valley by sharp and steep dividing ridges. Valley side slope angles are greatest at the headwaters of each valley, and tend to decrease towards the coast, especially where the regolith mantle is thickest. Each valley has a small alluvial plain of around 1km in length and 500 to 800m in width (Figs. 2.3 and 2.4).

The Purau and Orton Bradley valleys were formed as erosion removed the soft conglomerates, lake sediments and pyroclastic materials which are still to be found in the upper reaches of these valleys. Rapid erosion within the Lyttelton crater is evidenced by breccia-conglomerates that underlie the youngest Mt Herbert lavas found on Quail Island Sewell, (1985). Further conglomerates, sandstones and

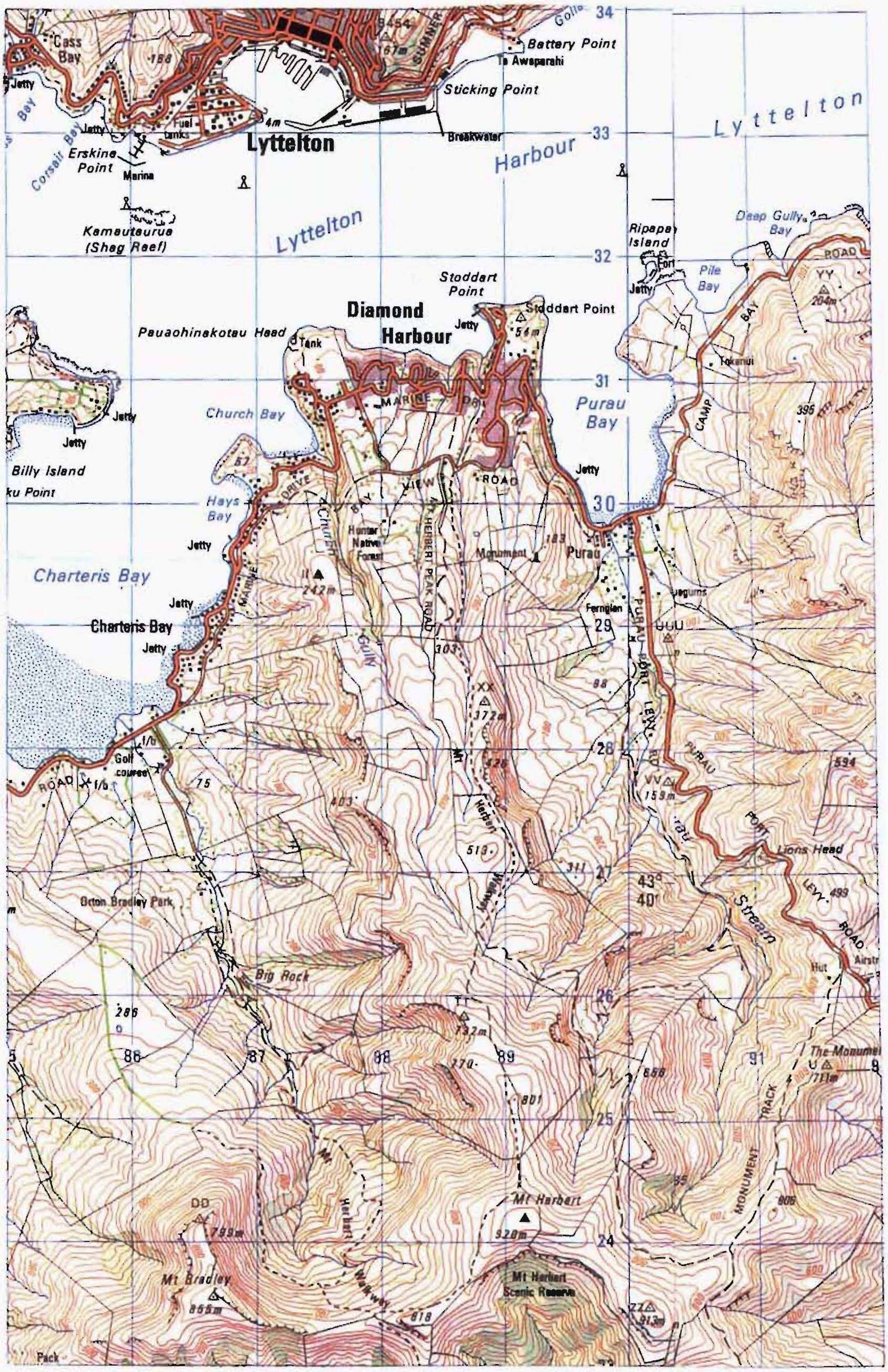


Fig. 2.2 Topographic map of the study area.

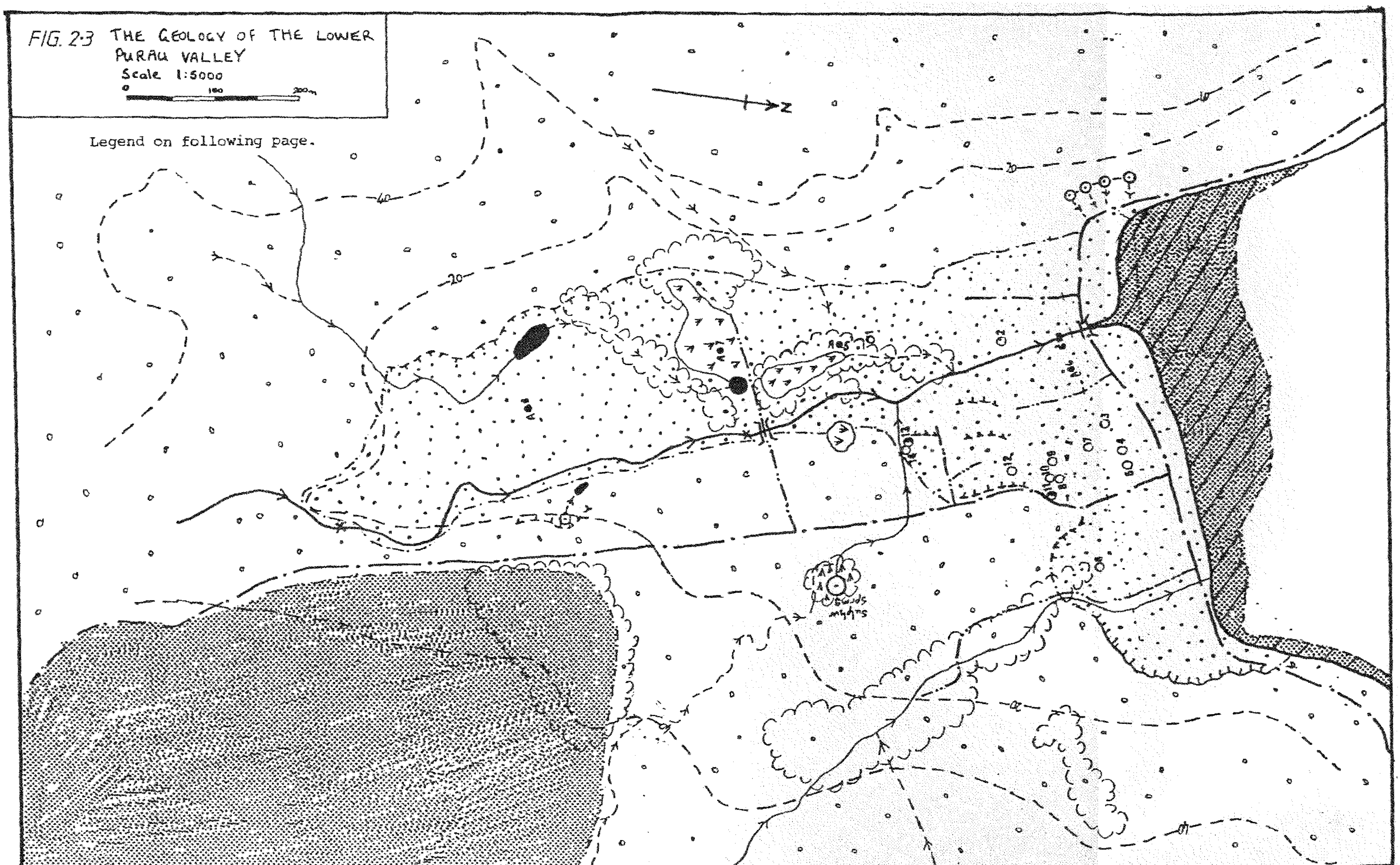
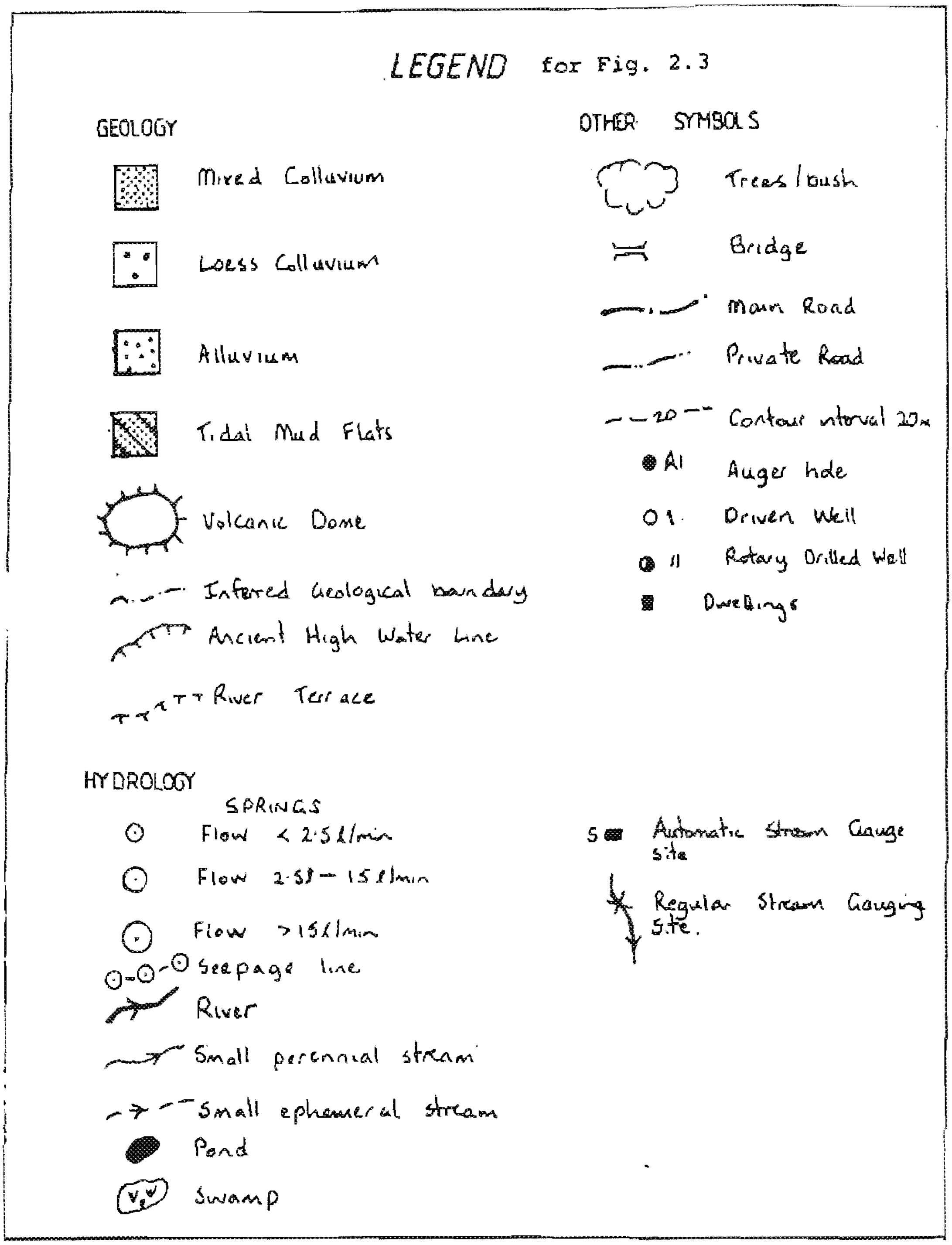


FIG. 2·3 THE GEOLOGY OF THE LOWER PURAU VALLEY

Scale 1:5000

Legend on following page.


LEGEND for Fig. 2.3
GEOLOGY
Mixed Colluvium
Loess Colluvium
Alluvium
Tidal Mud Flats
Volcanic Dome
Inferred Geological boundary
Ancient High Water Line
River Terrace
HYDROLOGY
SPRINGS
Flow < 2·5 l/min
Flow 2·5l – 15 l/min
Flow > 15 l/min
Seepage line
River
Small perennial stream
Small ephemeral stream
Pond
Swamp
OTHER SYMBOLS
Trees/bush
Bridge
Main Road
Private Road
20
Contour interval 20m
A1
Auger hole
1
Driven Well
11
Rotary Drilled Well
Dwellings
5
Automatic Stream Gauge site
Regular Stream Gauging site.

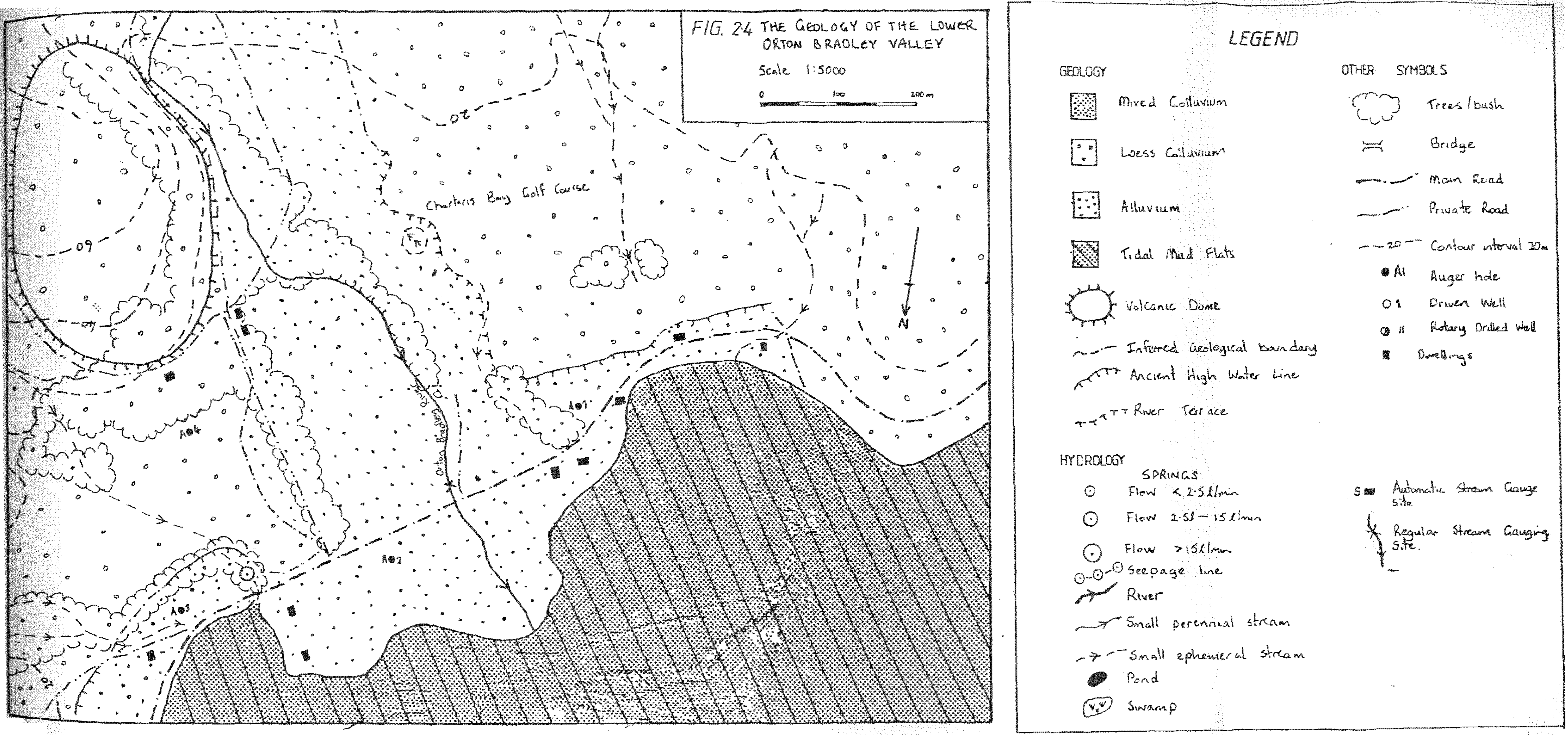


FIG. 24 THE GEOLOGY OF THE LOWER ORTON BRADLEY VALLEY

mudstones are found associated with the Church Basalts, suggesting continued rapid erosion within the Lyttelton crater. This suggests that both the the Orton Bradley and Purau valleys were forming up to 8 Ma ago.

Early Stoddart lavas were erupted as channel fill sequences in Kaituna Valley and Port Levy, also suggesting that these major valley systems had formed by 5.8 Ma (Sewell, 1985).

Separating both valleys is a feature known as the Diamond Harbour dip slope. This slope is narrow near Mt Herbert and widens to about 1.5km at the coast where it ends abruptly as a coastal cliff. The dip-slope represents the remains of the youngest volcanic lavas in the area and shows a juvenile drainage pattern. These youngest lavas post date the formation of the Purau and Orton Bradley Valleys.

In places along the flanks of the Dip slope, cliffs have developed where joint controlled lavas have failed, the eroded materials forming talus slopes. A notable feature found in both valleys are the flat lava benches that probably formed by erosion of pyroclastic interbeds. These benches are often associated with volcanic springs.

Many deeply incised tributary streams feed the Purau and Orton Bradley rivers. The perennial streams among them derive all their base flow from bedrock volcanic springs.

2.4 REGOLITH MATERIALS AND THEIR DISTRIBUTION

2.4.1 Terminology

To remain consistent with other writers who have investigated the occurrence of groundwater on Banks Peninsula, Yetton (1983), Sanders (1986) and Namjou (1988), the following classification of regolith materials based on Bell and Trangmar (1987), has been used in this study. The different types and distribution of regolith materials were found to have an influence on spring distribution and morphology within the study area (Fig. 2.5).

Bell and Trangmar (1987) have classified surfical deposits according to five types. The term colluvium here describes regolith materials deposited on a slope as a result of erosion processes: the prefix loess- or volcanic- indicates the dominant component (>90% by volume) in the colluvium, whilst the deposits with less than 90% of each material are referred to as mixed. The term regolith describes materials derived from the in situ weathering of volcanic bedrock.

1) in-situ (primary airfall) loess	
2) loess colluvium	less than 10% (by volume) volcanic fragments
3) mixed deposits of loess and volcanic derived colluvium	the ratio of each constituent part varies from 10% to 90%
4) volcanic colluvium	greater than 10% volcanic fragments
5) Residual Regolith	greater than 90% volcanic material from in-situ weathering

2.4.2 In-situ Loess and Loess Colluvium

a) Composition

Of the two facies of Loess mapped by Griffiths (1973) only the Barrys Bay facies is present in the study area. In-situ (airfall) Loess is composed predominantly of quartzofeldspathic minerals with minor accessory minerals (eg epidote, zircon and tourmaline), and some secondary clay minerals such as illites and vermiculites.

Loess colluvium consists of in-situ loessial deposits transported downslope. It is composed of clayey silt materials with some fine sands and the addition of up to 10% volcanic rock fragments, which can vary from sand sized particles to boulders (Plate 2.1).

b) Distribution

Bell and Trangmar (1987) have produced an idealised model relating regolith type to landform and slope angle. This model was found to be generally applicable to the study area (Fig. 2.6), and was used along with field observations to define the general distribution of all regolith types.

In-situ loess deposits are mainly found in footslope positions and in Charteris Bay thicknesses of 6-8m have been observed at low altitudes. Elsewhere on Banks Peninsula thicknesses of up to 15m have been observed. No in-situ loess deposits were observed, on ridge tops, however as is suggested by Fig.2.6, but some in-situ loess deposits have been exposed in deep failures on lower bankslope positions where they have been buried by colluvium (Fig. 2.5).

Loess colluvium occurs on the toe slopes, footslopes and some backslopes in the study area. Where preferential erosion of softer materials has occurred (eg tuffs or Lake deposits), the resulting flat benches have facilitated the accumulation of loess colluvium at higher altitudes.

2.4.3 Mixed Colluvium

a) Composition

Mixed colluvium consists of loess colluvium mixed with the weathering products of volcanic outcrops derived from upslope. The ratio of loess colluvium to volcanic colluvium

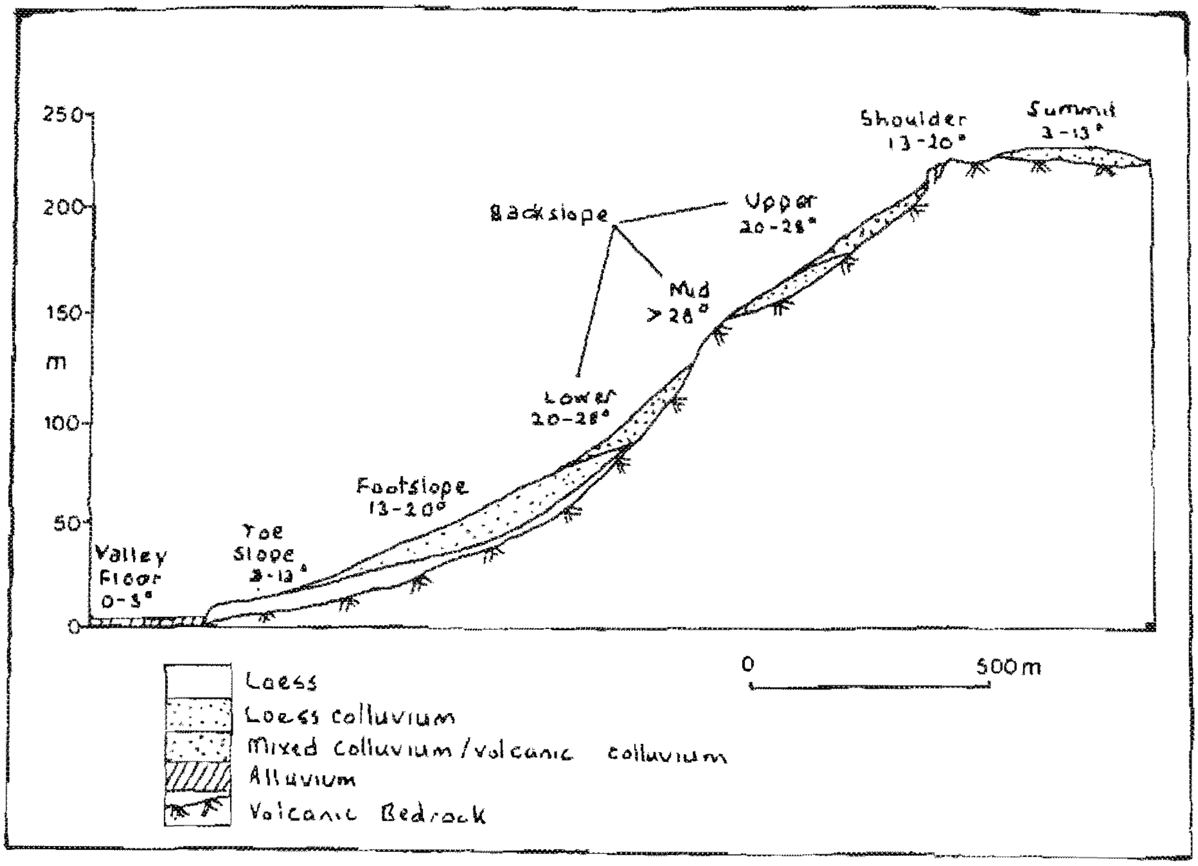


Fig. 2.6 Idealised regolith slope distribution in Diamond Harbour. (after Bell and Trangmar, 1987)

varies from 10% to 90%, and as a result the morphology of mixed colluvium is highly variable. The volcanic fragments range from sand sized particles to boulders (Plate 2.2).

b) Distribution

Mixed colluvium occurs on backslopes and upper footslopes. In the study area deposits can be generally divided into two types, viz 1) Those that contain 40-90% volcanic rock fragments (usually on mid to upper backslopes near rock outcrops), or 2) those that contain lesser amounts, (10-40%), of highly weathered volcanic fragments that appear as orangish particles within the predominantly loess deposit. These weathered fragments can easily be crushed by finger pressure. Often several layers of different morphology can be seen in outcrop separated by dark, buried topsoil layers representing several slope forming episodes. Thicknesses of up to 2.4m have been observed for mixed colluvium in the study area.

2.4.4 Volcanic Colluvium

a) Composition

Volcanic colluvium consists of volcanic weathering products containing up to 10% of loess derived materials. Volcanic colluvium is also highly variable, the ratio of coarse rock fragments to fines differing from place to place. Rock fragments can be unweathered to highly weathered. Two types predominate, viz 1) where weathering occurs by rock- fall and topple failure (for example, along the flanks of the dip- slope) the volcanic colluvium is almost entirely composed of gravel to boulder sized blocks of volcanic rock, or 2) where tuff cones and other pyroclastic deposits occur the volcanic colluvium consists

Plate 2.1 A typical exposure of loess colluvium over a weathered ash horizon in the lower right of the photograph. (N36 GR 903236)

Plate 2.2 A typical exposure of mixed colluvium with the volcanic component consisting angular to subrounded clasts. (N36 GR 912248)

of mainly sand to silt sized weathering products.

b) Distribution

Volcanic colluvium occurs mainly on moderately steep mid-backslopes but is also be found adjacent to most outcrops of volcanic rock regardless of slope position. Several slope forming episodes may be represented in a single deposit by several layers of different morphology. Thicknesses of up to 1.5m have been observed for volcanic colluvium in the study area.

2.4.5 Residual Regolith

Residual regoliths are formed by the in-situ weathering of volcanic bedrock and consist of reddish brown, silty clay loams with up to 20% sand to fine gravel sized volcanic fragments. Residual regoliths are found on low angle slopes, often near ridge tops, and do not form extensive deposits. Thicknesses of less than a metre are observed. Residual regoliths only occur in small isolated pockets and have been mapped as volcanic colluvium.

2.4.6 Alluvial Deposits

Alluvial deposits exist in both the Purau and Orton Bradley valleys, and the following is a brief summary of their type and distribution. A more detailed discussion on alluvial deposits is presented in Chapter Three.

a) Orton Bradley Valley

The alluvium in the Orton Bradley Valley varies in total thickness from approximately 3 to 5m. At its inland limit, (M36 GR 863276), the alluvium consists of reworked loess derived materials which can be described as yellowish orange - grey, massive, fine sandy clay/ silt with some coarse sands and fine gravels, (Figs. 2.4 and 2.7). This deposit immediately overlies bedrock and is approximately 3m

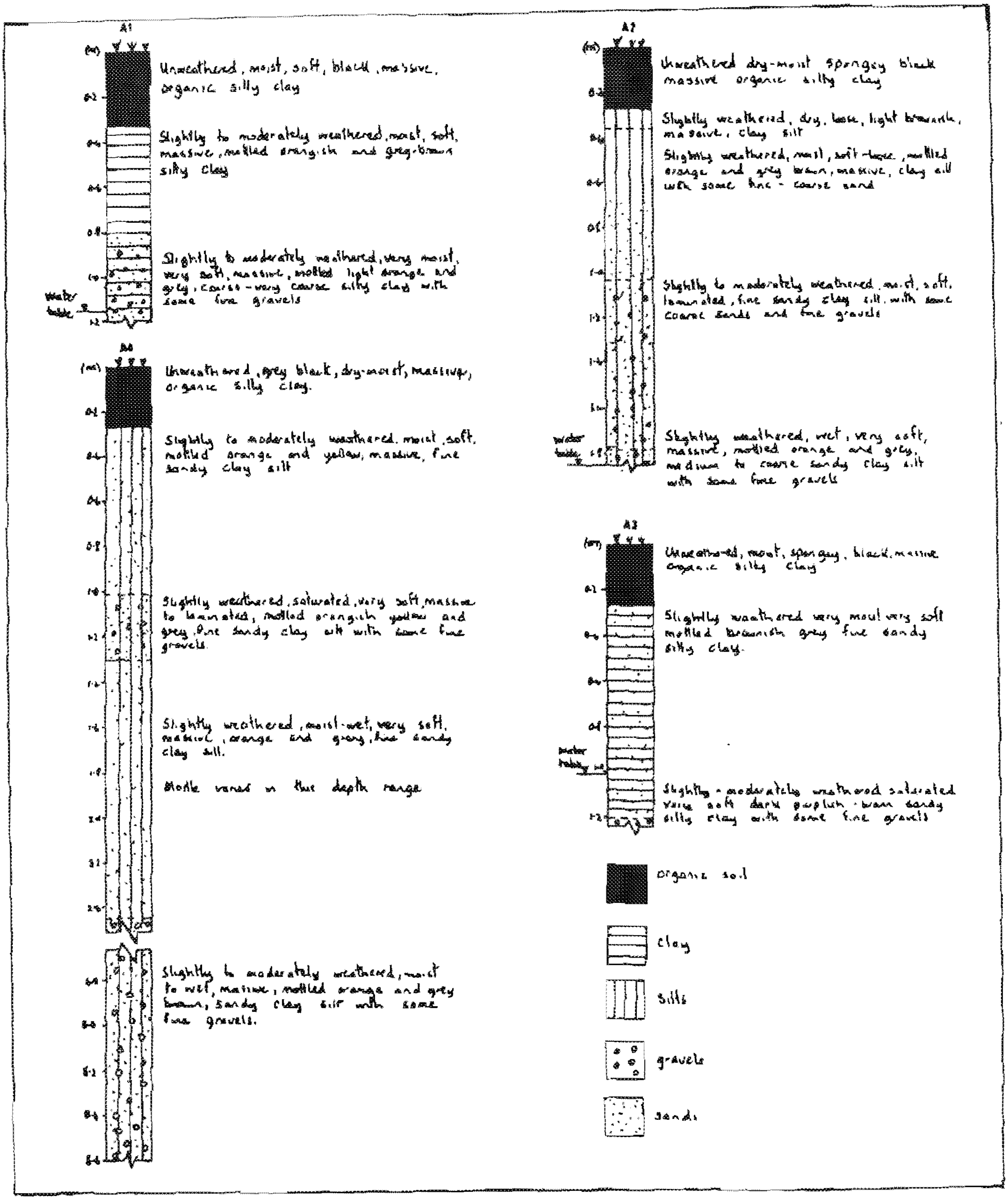


Fig. 2.7 Auger hole logs from Orton Bradley Valley

in thickness. At M36 GR 861280 a 1.75m gravel layer is sandwiched between river deposited clays and silts. The morphology of this gravel is unknown. The gravels increase in thickness (approximately 3m) to the north, GR 860282, where they appear to immediately overly volcanic bedrock. At the coast the gravels are overlain by an approximately 1.4m thick variable, yellowish to grey, bedded, sandy clay-silt, with an increasing gravel fraction as thickness increases. Some shallow (less than 2m) dug wells have intersected these gravels near the coast and have provided useful quantities of water for individual households.

b) <u>Purau Valley</u>

The alluvial deposits in Purau Valley vary in total thickness from approximately 10m at (M36 GR 899291) to approximately 13m near the coast at (M36 GR 900298), (Figs. 2.3, 2.8 and 2.9). The upper Purau Valley sediments consist of brown/yellowish to blue/greyish massive silty clays with some sands and fine to coarse volcanic derived gravels. These sediments are thought to represent swamp deposits, the coarse sediments being deposited during periods of flooding.Infilled river channels consisting of sandy gravels may be found within these swamp deposits.

The lower Purau Valley deposits represent a sequence of terrestrial and marine sediments which are the result of fluctuating sea levels (one to two metres at the most - R. Kirk, pers. comm.) over the past 6000 years or so. No radiocarbon dating was available to confirm this date. These deposits consist of infilled river channels, overbank muds and coastal marine muds. Immediately overlying volcanic bedrock in the lower Purau Valley is a sequence of brownish yellow, silty clays with some sands and fine gravels approximately 4 to 4.5m in thickness (Figs. 2.3, 2.8 and 2.9). Within these overbank muds can be found one or possibly more infilled river channels containing sandy fine gravels. These sandy gravels are grey, slightly weathered, angular to rounded, and represent the weathering products of

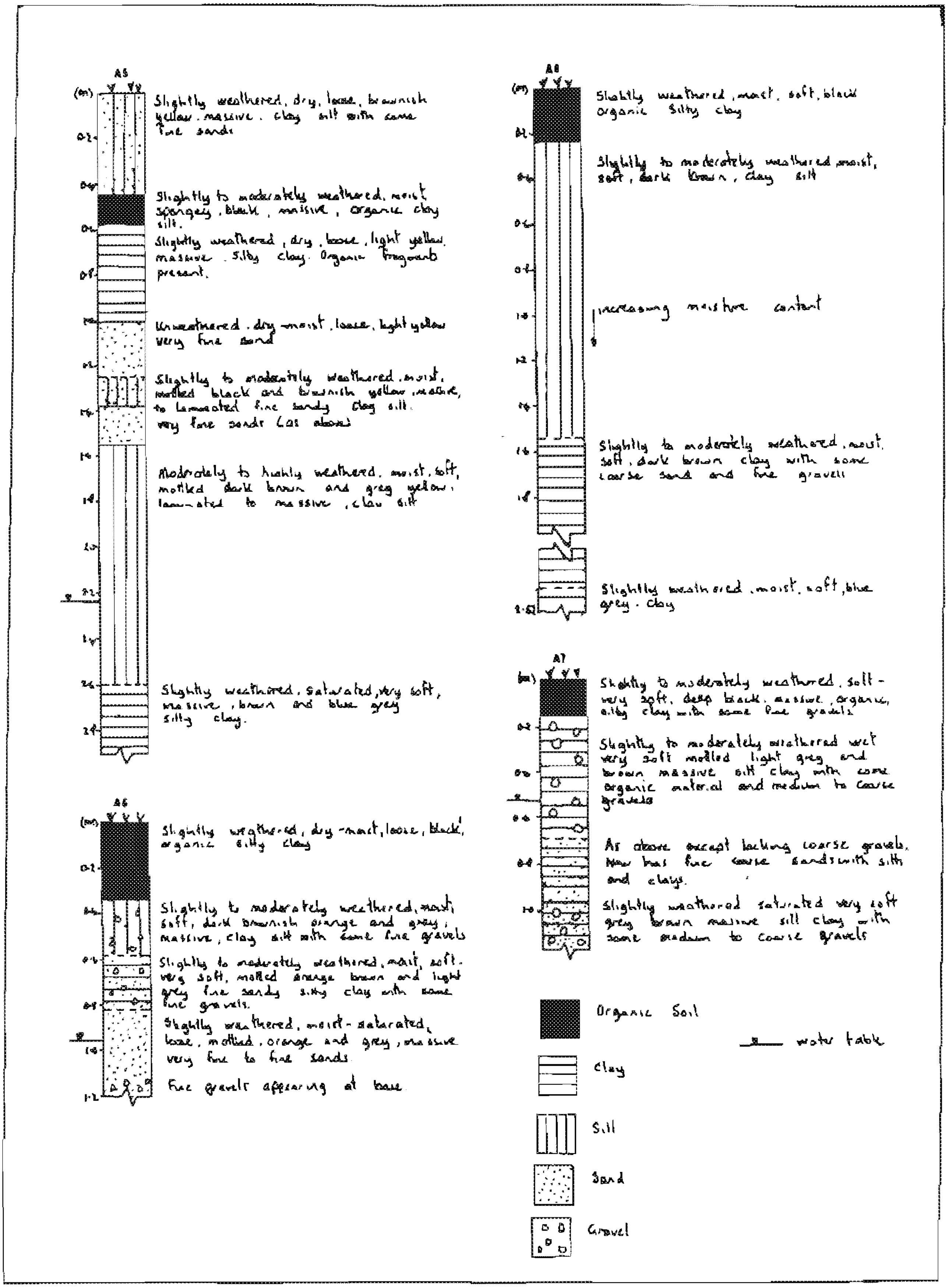


Fig. 2.8 Auger hole logs from the Purau Valley

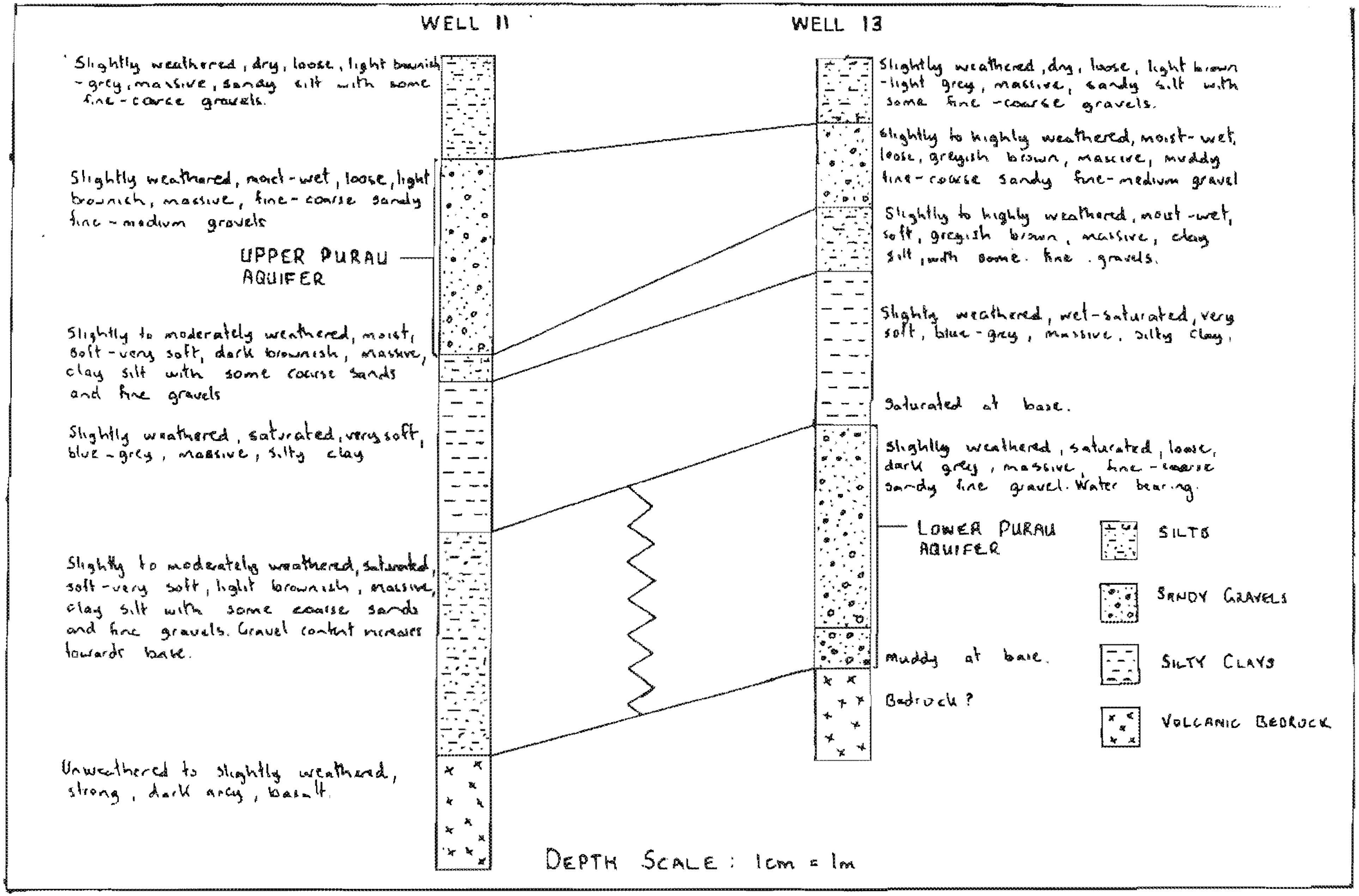


Fig. 2.9 Drillers logs for Wells 11 and 13 (Purau Valley)

local massive lava flows. While some clasts are rounded, most are angular to sub-angular. The sandy gravel unit represents the main aquifer in Purau Valley and provides locally significant amounts of groundwater to the Purau Motor Camp and for a few houses fortunate enough to overlie the aquifer.

Overlying the river muds and sandy gravels is a marine-estuarine blue-grey, silty clay of approximately 2 to 3m thickness. This unit is only present in the lower Purau Valley. A bedrock profile map (fig. 2.10) shows that a sea level rise of 1 to 2m would only have inundated the lower half of the Purau Valley.

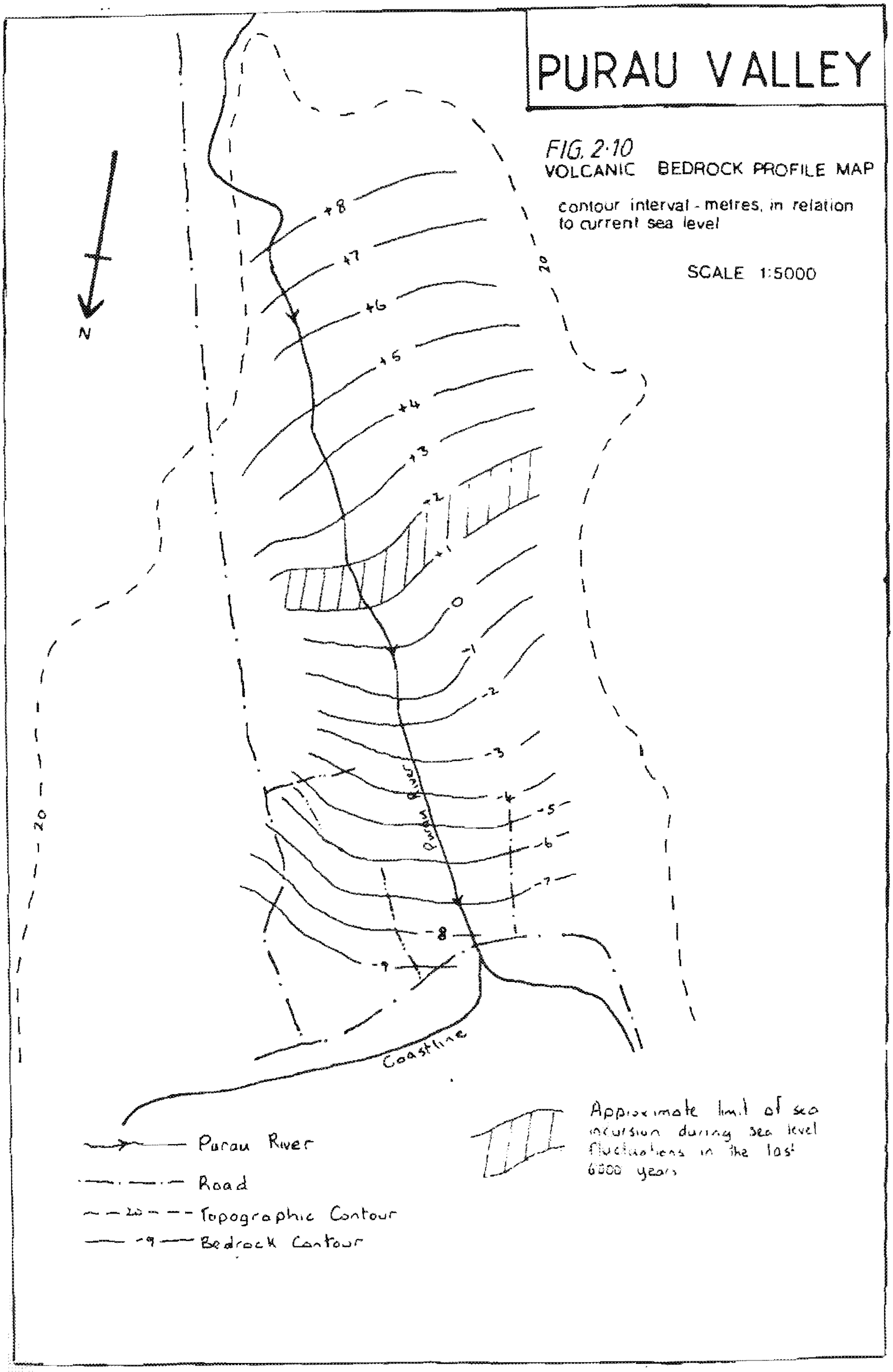
A second more laterally extensive layer of river sands and gravels overlies the marine muds, but is again, only present in the lower Purau Valley, (Figs. 2.3, 2.8 and 2.9). In places this unit has a muddy base. The sands and gravels are angular to rounded, but more evenly distributed between these extremes compared to the lower sands and gravels. The upper sands and gravels are distinctive from the lower sand/gravel unit in that they can be slightly to highly weathered, and in some locations have clearly been exposed to sub-aerial oxidation.

The upper sand/gravel unit is not saturated in all the locations where it is found, but is used as a shallow source of groundwater by some residents of Purau Valley.
Overlying this second sand/gravel layer on the surface is a thin bouldery river silt layer representing a modern flood plain deposit.

2.5 GROUNDWATER ON BANKS PENINSULA

2.5.1 Introduction

To date there have been four studies, including this one, that have specifically examined the groundwater resources on Banks Peninsula. The studies of Yetton (1983)


PURAU VALLEY
FIG. 2·10
VOLCANIC BEDROCK PROFILE MAP
contour interval - metres, in relation to current sea level
SCALE 1:5000
N
+8
+7
+6
+5
+4
+3
+2
+1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
20
20
Purau River
Coastline
Purau River
Road
Topographic Contour
Bedrock Contour
Approximate limit of sea incursion during sea level fluctuations in the last 6000 years

and Sanders (1986) specifically dealt with volcanic springs in the Port Levy, Pigeon Bay and French Farm regions of Akaroa County whilst Namjou (1988) examined both the volcanic springs and the groundwater found in the alluvial gravels of Kaituna Valley. The following discussion provides a brief summary of the findings of these writers, and serves as a framework on which to build the findings of the current study.

2.5.2 Geological Occurrence of Springs

a) Spring Morphology

It has been recognised that springs of two morphologies exist on the Peninsula, viz 1) Springs that have a confined outlet where flow exits from highly permeable layers such as jointed lavas, fractured soil horizons or erosion cavities in soils (Plate 2.3); and 2) diffuse springs where flow exits to the surface over a wide area (Plate 2.4). Both Sanders and Namjou suspect that the low permeability of some regolith materials is responsible for the occurrence of diffuse springs.

b) Spring Distribution

Lines of springs often occur at discrete levels tracing lava flow dips and indicating bedrock control of spring distribution (Sanders, 1986). These contact springs occur where permeable rock units (eg jointed lavas) overlie units of lower permeability (eg tuffs or massive unjointed lavas), or are colluvial springs relating to bedrock derived groundwater. Geomorphic benches may be associated with spring distribution in some areas. These benches are usually composed of erosion resistant materials and act as a trap to groundwater, hence the often large numbers of springs that occur at the scarp edges.

At lower altitudes the regolith cover tends to increase in thickness and spring numbers decrease. The distribution

Plate 2.3 A bedrock spring with a confined outlet found in the upper Purau Valley. The perching horizon here is a well cemented lahar. (N36 GR 902238)

Plate 2.4 An example of a diffuse spring outlet covering about $200m^2$ located in the upper Purau Valley. (M36 GR 899243)

of these lower altitude springs is often unclear, but most probably is related to the morphology of the slope deposits. Where more permeable horizons overlie less permeable horizons, (eg a relatively permeable volcanic colluvium layer overlying a less permeable loess colluvium layer), this may account for the distribution of some springs.

c) Groundwater Movement in Bedrock Aquifers

The principal aquifers identified in these studies are the anisotropic, variable jointed, coherent lava flows and their associated brecciated layers. Lavas typically are extruded in the aa condition where cooling occurs as the flow moves downslope. A crust forms on the top of the flow which is broken into discrete blocks as the less viscous, liquid, flow centre continues to move. This rubble may fall and form a carpet over which the flow then moves, (Fig. 2.11).

Basal breccias have been found to be thinner and less continuous than the brecciated tops of lava flows. The fragmented perimeters of lava flows grade into the more coherent lava centre, where some form of jointing and occasionally vesicularity are developed. Generally, jointing is variable within volcanic formations and often within individual flows themselves. Joint character relates in part to flow thickness and also to distance from chilled margins, with joint intensity at its greatest near the flow margins.

Two joint sets are typical, one set perpendicular to the flow boundaries and another sub-parallel with the flow boundary. Joint spacing varies from 0.1 to 4m, the sub-horizontal set commonly being more closely spaced than the vertical set. Apertures of up to 0.3m have been observed,although weathering in places has reduced joint aperture by the infilling of weathering products.

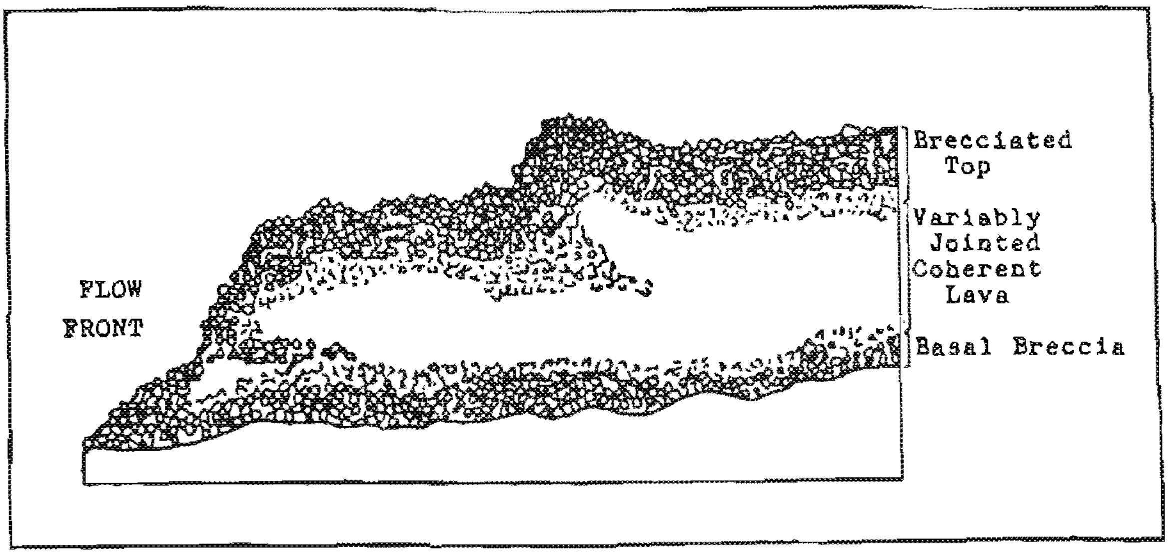


Fig. 2.11 Cross section through typical aa basalt lava flow
as preserved in Diamond Harbour. (After Weaver et al, (1985)

Hydraulic conductivities must vary in lava aquifers depending on factors such as joint spacing, aperture, weathering etc, and no figures are available for Banks Peninsula lavas. Freeze and Cherry (1979), quote a range of valves from 10^{-9} to 10^{-2} m/s, and clearly it is secondary porosity and permeability that determines how well a lava flow will transmit and store groundwater, and hence its importance as an aquifer.

The best aquifers found on Banks Peninsula tend to be unweathered basalt flows. Cooling joints provide the main vertical flow path, while sub-horizontal joint sets or clast supported basal breccias and unweathered and uncompacted rubbly tops (where interstitial fines are not well developed) are the most efficient media for lateral water transmission (Figs. 2.12 and 2.13).

d) Barriers to Groundwater Movement

Highly weathered jointed lavas, pyroclastic materials, tightly jointed or massive lavas, welded or weathered scoria and weathered rubbly lava tops, are seen to be effective barriers to groundwater movement on the Peninsula. Where present these form perching layers to groundwater bodies, particularly at higher altitudes.

Irregular thicknesses of pyroclastic materials of up to 4m have been observed in Akaroa County, Kaituna Valley and Port Levy. As there is frequently lateral variation in thicknesses of all types of perching layer, a series of leaky, perched aquifers exist where groundwater can readily percolate to a lower groundwater body.

Both Sanders (1986) and Namjou (1988) suggest that radial dyke swarms probably act as vertical barriers to groundwater movement although they found no evidence for this in the field.

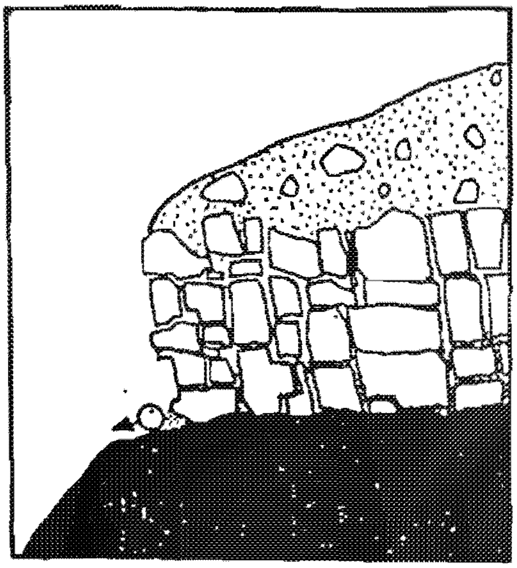


Fig. 2.12 Schematic diagram: spring issuing from jointed lava where this overlies tuff layer (solid black in diagram). Mixed colluvium overlies the jointed lava. (From Sanders, 1986)

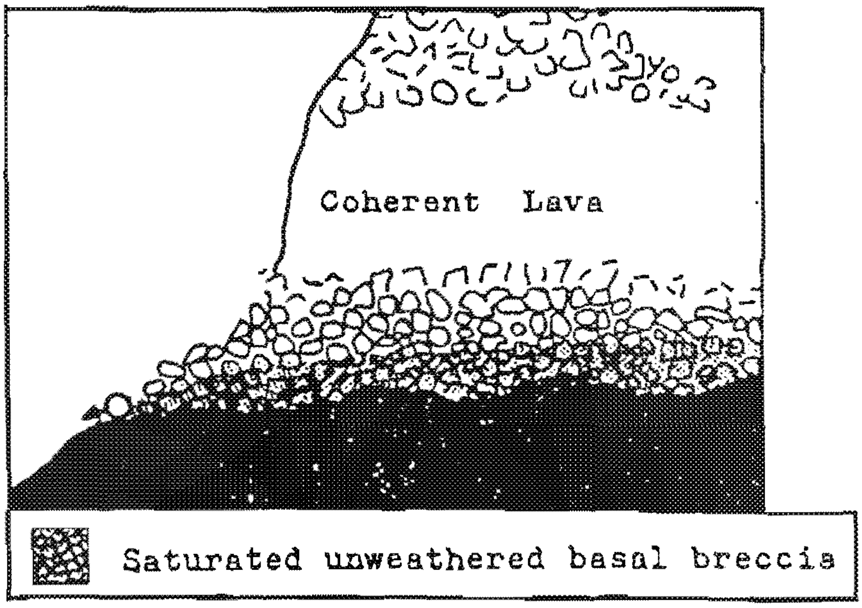


Fig. 2.13 Spring emerging from unweathered basal breccia where this overlies relatively impermeable layer, eg tuff.
(From Sanders, 1986)

e) Groundwater Movement in Surfical Materials

All previous writers agree that surfical deposits usually confine groundwater flowing from volcanic aquifers, and in the process may become a medium for transmission of water to the surface. The finer materials, in particular, may act as a capping layer over bedrock preventing groundwater movement to the surface.

Mixed and volcanic colluvial springs appear to be the most common due to the extensive cover of these materials on Banks Peninsula. Groundwater for mixed and volcanic colluvial springs is derived from volcanic bedrock aquifers and/or direct infiltration.

Springs occur where groundwater is forced to the surface at the edges of geomorphic benches or where the surfical cover thins. Both confined and diffuse springs emerge form these colluvial types. Sanders (1986) derived hydraulic conductivities of 1.1×10^{-5} to 1.6×10^{-7} m/s for mixed and volcanic colluvium, these values most probably being derived from colluvium with a low coarse/fines ratio. He suggests that of all colluvial types, volcanic colluvium will have the highest infiltration rates, although this will depend on the ratio of coarse to fine material (Figs. 2.14 and 2.15).

Fewer springs emerge from loess than mixed or volcanic colluvium. These springs tend to be found at lower altitudes and have relatively low discharges. Springs emerging through loess tend to be diffuse because of the generally massive nature of loess materials, their relatively low hydraulic conductivity (10^{-6} to 10^{-7} m/s), and the generally low slope angles of these deposits. More confined springs are found where fracturing and tunnelling are present. Water tends to move along zones of contrasting permeability such as the C-layer fragipan or the loess-bedrock boundary, (Figs. 2.16 and 2.17).

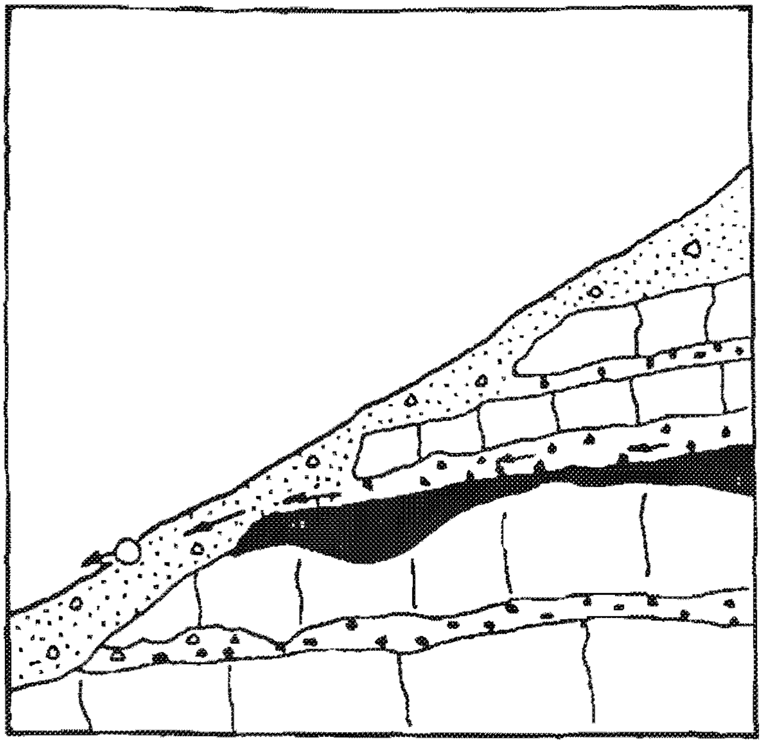


Fig. 2.14 Mixed or volcanic colluvium spring due to input of water from bedrock aquifer. Arrows show flow path of water from basal breccia overlying tuff bed (solid black) out into colluvium. (From Sanders, 1986)

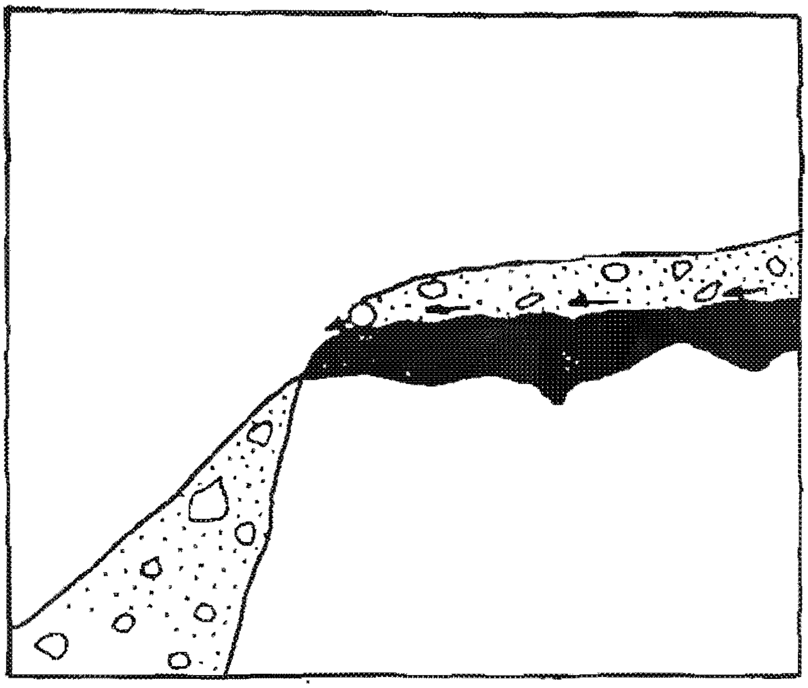


Fig. 2.15 Mixed or volcanic colluvium spring where colluvium thins over change in slope in underlying volcanics. Arrows depict possible flowpath through colluvium above tuff layer (solid black). (From Sanders, 1986)

2.5.3 Groundwater in Alluvial Coastal Sediments

a) Introduction

Neither Sanders (1986) nor Yetton (1983) looked in detail at the shallow alluvial sediments found in the valleys of their respective study areas. They commented briefly on the presence of alluvial springs, but it seems that only the larger valleys on the Peninsula have the thicknesses and extent of alluvium where it would be likely to encounter groundwater, (eg Purau Valley, Kaituna Valley, and Little River Valley).

b) Kaituna Valley

Some of the larger valleys on the Peninsula clearly do have considerable thicknesses (up to 175m in Kaituna Valley) of alluvial sediments. Namjou (1988) found that Kaituna valley was an ancient valley system which began forming up to c. 10 Ma ago. The valley is now infilled with a wedge of sediments resting on a southward dipping surface of volcanic bedrock. During post glacial times (12,000 to 2,000 years BP) alternating transgressive and regressive sediments were deposited within Kaituna Valley in response to sea level fluctuations. The marine and terrestrial sediments consist of poorly sorted volcanic rubble, beach gravels, fine grained lagoonal muds and clays, along with terrestrial gravels, silt, clay and sandy silts.

Two aquifers have been identified by Namjou (1988) in the Kaituna valley, the lower one immediately overlying the volcanic bedrock and consisting of gravel and volcanic colluvium. This aquifer is confined by marine clay deposits. The thickness of the lower aquifer depends on the volcanic bedrock topography but seems at its greatest (about 15m) in the buried river channels.

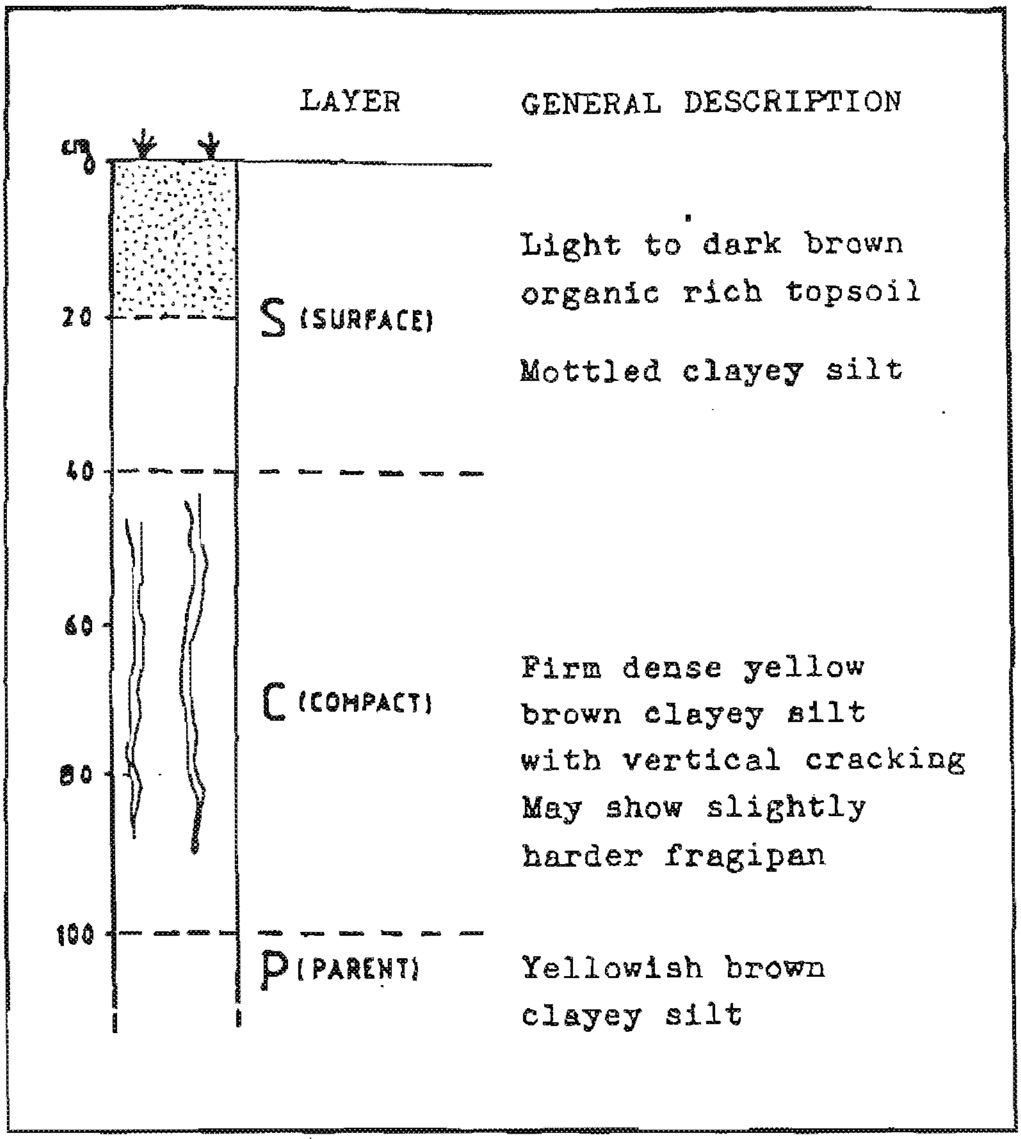


Fig. 2.16 Schematic profile in loess of Diamond Harbour (after Sanders, 1986)

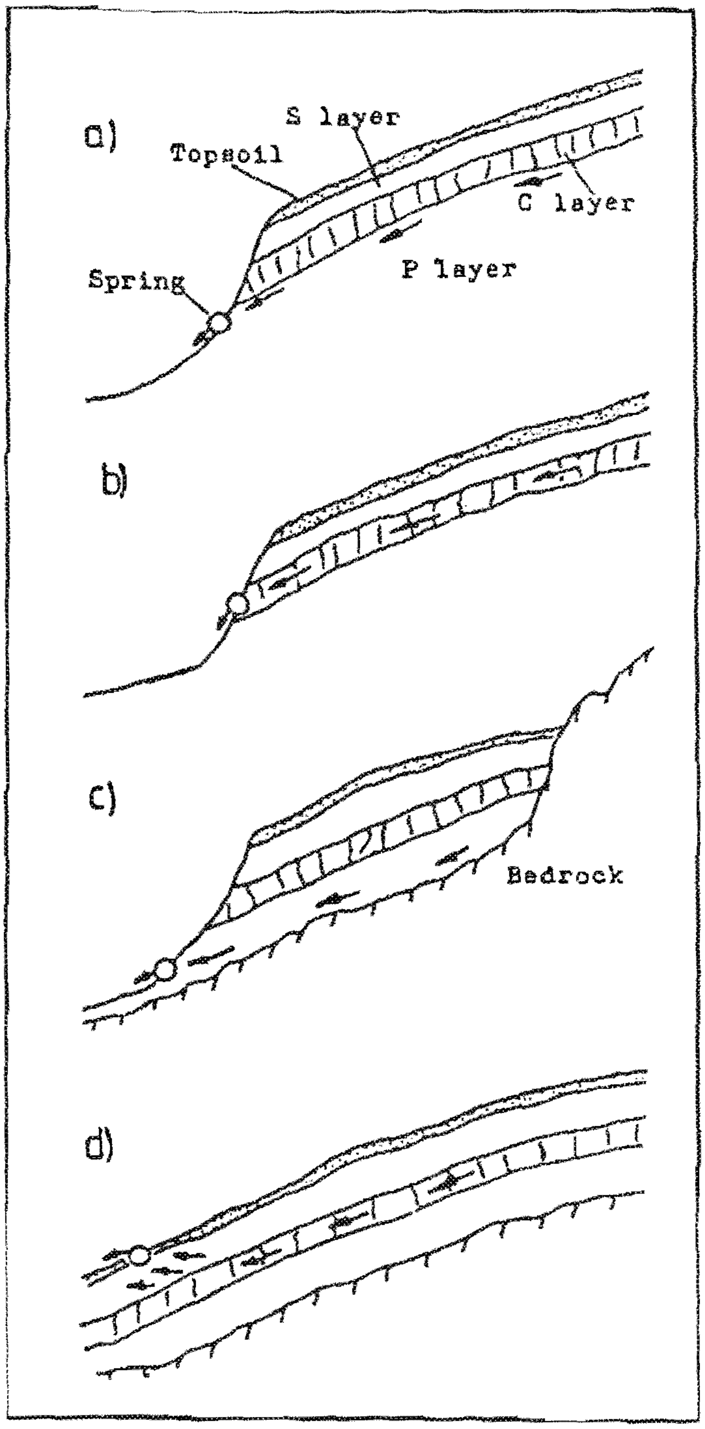


Fig. 2.17 Loess spring models.
a) spring occurs where water flowing in loess P layer intersects ground surface. Confined springs result when tunnels develop.
b) spring due to water perched above C layer fragipan.
c) loess spring at bedrock interface.
d) diffuse spring where water seeps to surface from, for example, above the C layer. (From Sanders, 1986)

An upper aquifer can be found in the shallow valley sediments present only in the lower part of Kaituna valley. It overlies fine sediments and is confined at its top by marine clays. This aquifer has an average thickness of 24m (Namjou, 1988).

Upper aquifer transmissivities range between 2×10^{-2} and 4.9×10^{-3} m^2/s, while lower aquifer transmissivities range between 4.8×10^{-3} m^2/s and 4.3×10^{-3} m^2/s. Safe yields for the lower aquifer were predicted at 12 l/sec when pumped for 24 hours. No figures for safe yields were given for the upper aquifer, but Namjou suggests they should be higher than those for the lower aquifer.

2.5.4 Environmental Isotope Studies

Both Sanders (1986) and Namjou (1988) used environmental isotopes to define groundwater residence times and to assist in making interpretations regarding the origin of Banks Peninsula groundwaters.

Both authors have interpreted the range of $\delta^{18}O$ and δD values for different spring and alluvial groundwaters to reflect the change in altitude of the recharging meteoric waters. Talbot (1986) found that high altitude precipitation from the Southern Alps has been found to have $\delta^{18}O$ values of between -9.0 and -9.8, and low altitude precipitation having values of -6.6 to -7.4. Values between -7.8 and -8.6 reflect precipitation from moderate altitudes. Values of ^{18}O from Akaroa County springs range between -7.1 and -8.0 (Sanders, 1986). Values of ^{18}O from Kaituna Valley groundwater range from -7.21 to -7.87 for water derived from alluvial aquifers, and -7.64 to -8.01 for spring water, (Namjou, 1988).

Regression lines of $\delta^{18}O$ and δD against altitude have been defined for Kaituna valley and Akaroa county. For Akaroa: (Sanders, 1986)

$$\delta^{18}O = 0.002h - 6.67, \quad \text{where } h = \text{altitude in metres above sea level}$$

For Kaituna valley: (Namjou, 1988)

$$\delta^{18}O = -0.0035h - 6.2, \quad \text{where } h = \text{altitude in metres above sea level}$$

Some waters deviate from these regression lines and a number of reasons for this are postulated. Spring water, originally precipitated at high altitude, could percolate, where geological conditions are favourable, to much lower altitudes, probably mixing with different waters as well. $\delta^{18}O$ and δD values do show slight variations seasonally. This may be a problem if sampling is carried out at different times of the year.

Namjou (1988) has shown from the use of the radioactive isotope tritium (^{3}H) that the mean residence times of the alluvial groundwater found in Kaituna valley ranges from 35 to 55 years, and that of local spring water is less than five years.

2.5.5 Groundwater Quality

a) Spring Waters

A large number of chemical tests have been carried out on spring water found on Banks Peninsula. The three authors previously mentioned, Yetton (1983), Sanders (1986), and Namjou (1988), have presented a total of nine analyses of spring water, and have made the following observations regarding potability and hydrochemistry.

1) Nearly all water from the Banks Peninsula volcanic springs studied so far can been classified as calcium-magnesium-bicarbonate water.

2) There seems to be a surprising variability among analyses considering the small area over which some of the samples were taken (Fig. 2.18). Most spring waters, however, were considered suitable as drinking water. Yetton (1983) considered this variability to reflect the wide range of hydrogeologic environments.

3) In general low pH values were obtained for spring waters, and for most, aeration would bring these to within acceptable limits. As a result of this acidity Sanders (1986) has suggested that metal water supply fittings will have relatively short lifespans,

4) All spring waters tested had nitrate nitrogen levels well below the New Zealand Standard limit of $10g/m^3$. This is taken to reflect the low levels of fertiliser application, typical of Banks Peninsula, and the absence of widespread intensive horticulture.

5) Chloride levels are on the whole within acceptable limits, the highest values being found in springs close to the sea. Sanders (1986) attributed this to possible sea spray contamination of groundwater.

6) Magnesium, sodium and iron concentrations tend to be high, some waters exceeding the desired limits. This is interpreted as ion leaching from basalt lava flows.

7) The majority of spring waters examined were soft to moderately soft with respect to total hardness (Table 2.2). The occasional spring had water in the slightly hard range, but the majority of spring waters have hardness values below the highest desirable limit.

b) Alluvial Groundwater

Namjou (1988) noted that well water found in Kaituna valley usually had higher concentrations of most ions than those found in local springs, (Fig. 2.19). Most well waters

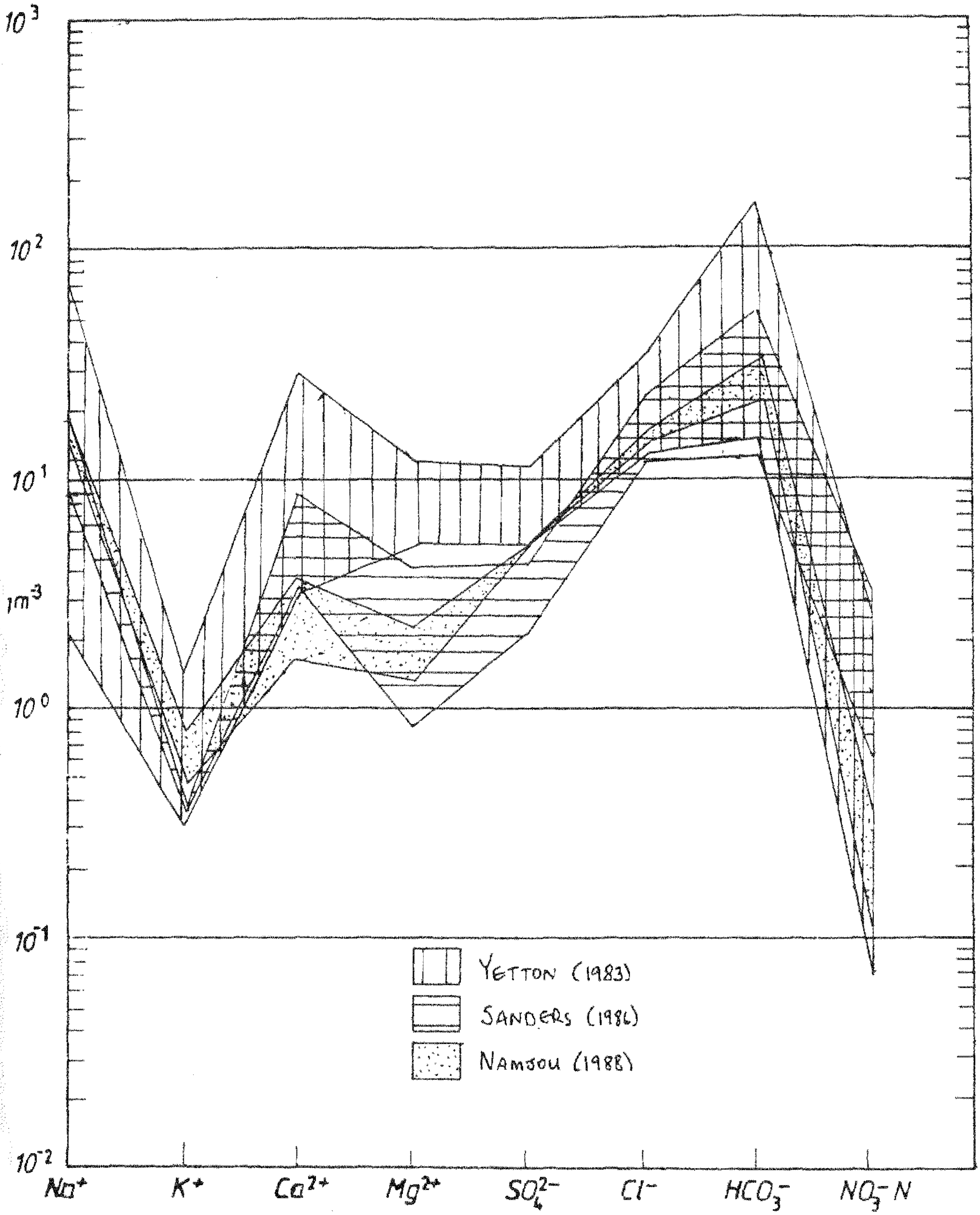


Fig. 2.18 Chemical profiles of spring waters from the studies of Yetton, 1983, Sanders, 1986 and Namjou, 1988.

50 ppm of hardness	soft
50 - 100 ppm of hardness	moderately soft
100 - 150 ppm of hardness	slightly hard
150 - 250 ppm of hardness	moderately hard
250 - 350 ppm of hardness	hard
350+ ppm of hardness	very hard

Table 2.2 Hardness criteria.

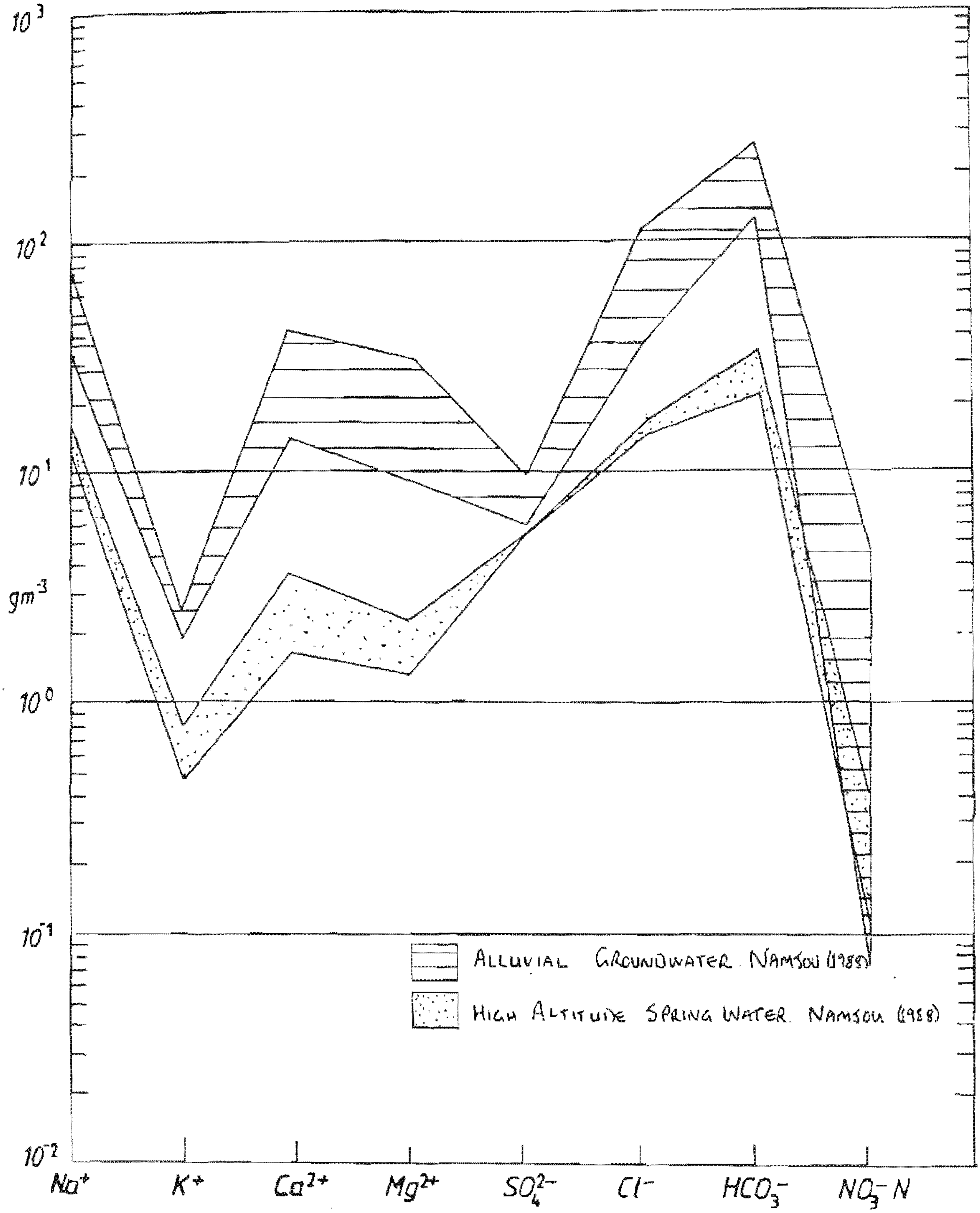


Fig. 2.19 Chemical profiles of the alluvial groundwater and the High Altitude Spring groundwater of Kaituna Valley.

had low nitrate nitrogen levels (<1 g/m^3) with the exception of one shallow well that had a moderate level (4.6 g/m^3) of nitrate - nitrogen, which was attributed to livestock urine spotting.

Kaituna valley well waters are moderately soft to moderately hard and all have iron concentrations that exceed the 'highest desirable' limits (NZ Board Of Health, 1984).

All well waters had low magnesium concentrations and sodium concentrations were below the 'highest desirable' limits set for New Zealand drinking water. Calcium values fall within acceptable limits.

Sulphate levels were found to be within acceptable limits but two bores were found to have chloride levels above the highest desirable limits. The water from all bores was found to have excessive bicarbonate content, and ranged from 129 to 269g/m^3.

c) Ion sources

Namjou (1988) briefly examined the origins of many of the ions found in both well and spring waters. He noted that ion concentrations in Kaituna waters could be accounted for by dissolution processes occurring when acidic meteoric water moved through fractures within volcanic rocks. Minerals such as plagioclase feldspar and magnesium/ iron rich olivines, when in the presence of acidic water are unstable and would weather slowly, leaving a clay mineral residue (Hem, 1959). Namjou also attempted to relate ion concentrations to the length of flow path individual water molecules had taken. He assummed that higher concentrations of ions indicated water had been moving within the volcanic rock for a longer period compared to water that had lower relative ion concentrations. His evidence for these conclusions was based on chemical and isotopic data.

2.6 SYNTHESIS

Ths study area consists largely of a group of Miocene volcanic rocks of the following groups: Lyttelton (11 to 9.7 Ma), Mt Herbert (9.7 to 8.0 Ma) and Diamond Harbour (7.0 to 5.8 Ma). Some rocks of the minor "Church-type" lavas are also found within the study area.

The study area consists of the eroded remains of the above volcanic groups now blanketed by airfall loess deposits, and combinations of loess and volcanic materials mixed together as a result of slope processes. Thin alluvial deposits (<15m depth) are found in the lower areas of both the Purau and Orton Bradley Valleys.

The study area represents two ancient valley systems (Purau and Orton Bradley Valleys) that began forming up to 8 Ma ago, separated by a long 'dip-slope' composed of the youngest Diamond Harbour Group lavas.

A summary of the work of Yetton (1983), Sanders (1986) and Namjou (1988) provides a background of previous groundwater investigations on Banks Peninsula, on which to base this current study.

The principal aquifers identified in the above studies are the anisotropic , variably jointed, coherent lava flows and their associated brecciated layers. Pyroclastic layers and massive unjointed lavas represent the main perching layers.

Studies of the Kaituna Valley have found that this valley is infilled with thicknesses of terrestrial and marine sediments deposited between 12,000 and 2,000 years BP. Two aquifers have been identified in this valley which represent infilled river channels of sandy gravels.

CHAPTER THREE

VALLEY FLOOR AQUIFER SYSTEMS

3.1 INTRODUCTION

One, and possibly more, thin (<4m thick) aquifers exist in the alluvium filling the lower Purau and Orton Bradley Valleys (Figs. 2.3 and 2.4). There are also deeper groundwater systems found in joint-controlled fractures within the local volcanic formations. Chapter Three details investigation techniques that were used to define and characterise the valley floor groundwater resource in the Purau and Orton Bradley Valleys, and the interpretation of these results. Discussion includes possible recharge sources for the valley floor aquifer systems, and also a section that relates the deep groundwater to that found in alluvial aquifer systems.

Geophysical downhole logging and electrical resistivity techniques were used to examine and delineate the sedimentary aquifers found in both valleys. Three wells in Purau Valley were downhole logged, the aim being to infer the physical parameters of the alluvial sediments and to enable correlation between different boreholes.

Three chemical analyses of the groundwater found in the lower Purau Valley were taken in August and September of 1988. A fourth sample was taken from a deep hard rock bore in the Orton Bradley. Each of these sources were also sampled for oxygen-18 and tritium to determine residence times and possible origins of the water.

A drilling programme involving the siting of two wells in Purau Valley on the basis of interpreted geophysical and pumping test information is also discussed in this chapter. Surface hydrogological data from the Purau river is also examined to determine any relationship between the surface and groundwater regimes of this valley.

3.2 GEOPHYSICAL WELL LOGGING

3.2.1 Methodology

Fourteen wells exist in the lower Purau Valley where alluvial deposits are found to vary from approximately 3 to 13m in thickness (Fig. 2.3). With the exception of two wells sited by the writer and drilled under supervision the other 12 wells are driven wells which consist of 37 to 50mm steel piping driven into the ground until they reach water bearing strata. Most have a one metre or so slotted section at the base to allow water extraction from the aquifer. As no geological information is gained when a driven well is put down, it was necessary to geophysically log these wells to gain any subsurface information from them. There were no wells in the sediments of the Orton Bradley Valley, hence the logging was limited to Purau Valley.

The aim of the geophysical well logging was to use caliper, natural-gamma, gamma-gamma and neutron-neutron logging techniques to determine lithological variations and characteristics so that correlation between boreholes could assist in the hydrogeological investigation. Unfortunately it was found that most of the bores were of such narrow diameter (<50mm) that the logging tools would only fit down three shallow bores. Appendix Four describes some of the theoretical considerations involved with geophysical logging. The three wells (well numbers 6,12 and 14, Fig. 2.3) were logged by M. Simpson, Senior Technician DSIR, assisted by the writer in February 1988.

1) Fine grained sediments usually have high concentrations of radioactive materials. The number of counts on a natural gamma log will, as a result of this radioactivity, increase with an increasing clay content. Sediments derived from an igneous source contain minerals such as feldspars which contain significant amounts of radioactive potassium-40. When logging sediments which are

all derived from an igneous source the contrasts between coarse and fine lithologies with the same mineralogy, will not be obvious because coarse and fine materials often emit similar radioactive signals.

2) Gamma-gamma give an indication of changes in apparent bulk density, where the count rate increases with decreasing with apparent bulk density.

3) Neutron-neutron logs reflect changes in apparent porosity where high neutron response is generally an indicator of low apparent porosity.

4) Correlations between low natural gamma signal and low apparent density, or high apparent porosity, could be caused by hole diameter changes or caving behind borehole casing. Natural gamma signal is unlikely to be related to hole size if a correlation exists between low natural gamma and high apparent density, or low apparent porosity (White, 1985).

3.2.2 Interpreted Borehole Logs for Purau Valley

Two drilled wells were put down in the lower Purau Valley as part of the hydrogeological investigation. One well (No. 11, Fig. 2.3) was privately funded, while the second well (No. 13, Fig. 2.3) was jointly funded by the NCCB and Purau Motor Camp owners. A private contractor (Mr G. Baikie) was employed using a rotary percussion drilling rig for both wells. Well 11 is a 100mm steel cased bore and well 13 is a 150mm steel cased bore.

a) Well 11 Interpreted Log

Figure 2.9 shows the correlated well logs for well 11 and well 13. Bedrock was found at 12.9m in well 11, and overlying bedrock is a sequence of dominantly fine grained sediments. These fine grained sediments consist of brownish clayey silts, usually with a minor sand and fine gravel fraction, and blue-grey silty clays. A layer of sandy gravels is present between 1.8 and 5.5m depth. This gravel layer was not water bearing in well 11, but it is known that shallow wells in other parts of the lower Purau Valley extract locally significant amounts of water from what is interpreted to be the same gravel. This gravel layer is known as the Upper Purau Aquifer where it is water bearing.

b) Well 13 Interpreted Log

A similar sequence of fine grained sediments and gravels is found in well 13 (Fig. 2.9). Volcanic bedrock was not reached in this well, the total depth of the well being 11.3m. It was decided not to continue this well beyond the lower gravel sequence as the costs involved in backfilling the hole below the aquifer were considered to be prohibitive. The same brownish clayey silts and blue-grey silty clays were found in well 13. An upper sandy gravel layer, muddy towards its base, is again present in the sequence. This layer is not water bearing and is interpreted to be the equivalent of the Upper Purau Aquifer. Below the blue-grey silty clays in well 13 is a 3.78m thick layer of clean water bearing sandy fine gravels (Fig. 2.9), and this layer is referred to as the Lower Purau Aquifer.

3.2.3 Interpretation of Geophysical Borehole Logs

a) Well 14, Purau Motor Camp

From the base of this hole at 6.6m to a depth of 5.8m is a layer characterised by low natural gamma count, low apparent density and high apparent porosity (Fig. 3.1). This zone is correlated with well 13 (Fig. 2.9) to be the gravel representing the Lower Purau Aquifer. The reason for the high apparent porosity and low apparent density of this layer is probably the removal of the sandy matrix by pumping to create a low density, highly porous gravel pack around the slotted area of pipe. Usually the reverse seems to be normal on the Canterbury Plains, where a saturated sand/gravel aquifer will have high apparent density and low apparent porosity relative to other sediments.

A layer with high natural gamma is present between 5.8 and 3.8m. This layer also shows higher apparent density and the lowest apparent porosity, and is interpreted to represent the compact blue-grey silty clay found in well 13.

A layer of slightly lower natural gamma signal and apparent density is represented between approximately 3.8 and 2.6m. Apparent porosity is slightly higher than in the underlying layer, and the unit is interpreted to represent the gravelly mud found in well 13 above the blue-grey silty clay layer.

A layer of increasing natural gamma count and low apparent density is found from 2.6 to 1.6m. This layer is above the water table and is interpreted to represent the muddy gravel (Upper Purau Aquifer) found in well 13. Above 1.6m is a thin surface layer of sandy silts.

b) Well 12, Les Gay Property

Represented between 7.7 and 6.3m is a layer of lower natural gamma, low to moderate apparent density and high apparent porosity. This is interpreted to be the Lower Purau Aquifer (Fig. 3.1). The upper 0.9m in this range appears to represent aquifer material which retains most of its sands, and hence has a higher apparent density compared to the lower portion of the aquifer where the sands have been removed by pumping. The slotted length is estimated to be 0.4m in length at the very base of the hole.

Between 6.3 and 5.6m is a layer showing increasing natural gamma, apparent density and decreased apparent porosity, which is interpreted to be the compact blue-grey silty clays found in well 13.

A layer of decreased natural gamma, apparent density and increased apparent porosity is represent between 4 and 2.3m. This layer is interpreted to represent the muddy gravels (upper Purau Aquifer) found in well 13. Above this gravel layer is a thin surface layer of bouldery silts.

c) Well 6, Smith Property

Well 6 is a shallow 4.3m deep hole, and only two lithologies are interpreted to be present (Fig. 3.1). From 4 to 3.5m a layer of low natural gamma, apparent density and high apparent porosity is represented. This in interpreted to be the Upper Purau Aquifer found in well 11 (Fig. 2.9). The gravels in this hole appear to have a low clay content and the high apparent porosity indicates that at this location the gravels are water bearing. Overlying the gravels is a layer of clays and silts.

3.3 RESISTIVITY SURVEYS

3.3.1 Data Collection and Analysis

a) Introduction

The aim of the resistivity survey was to obtain subsurface hydrogeological and lithological information in the Orton Bradley and Purau Valleys. It was hoped that enough subsurface information could be gained to interpret depth to bedrock, and if possible to locate and delineate the known aquifer in Purau Valley. A similar aquifer was thought to exist in Orton Bradley Valley and an attempt to locate and delineate this aquifer was made using the resistivity method. The resistivity investigation consisted of a total of 15 Schlumberger array soundings, ten in Purau Valley and five in the Orton Bradley Valley (see Figs. 3.2 and 3.3).

The field survey was carried out by M. Simpson, Senior Technician, DSIR, assisted by the writer, using the

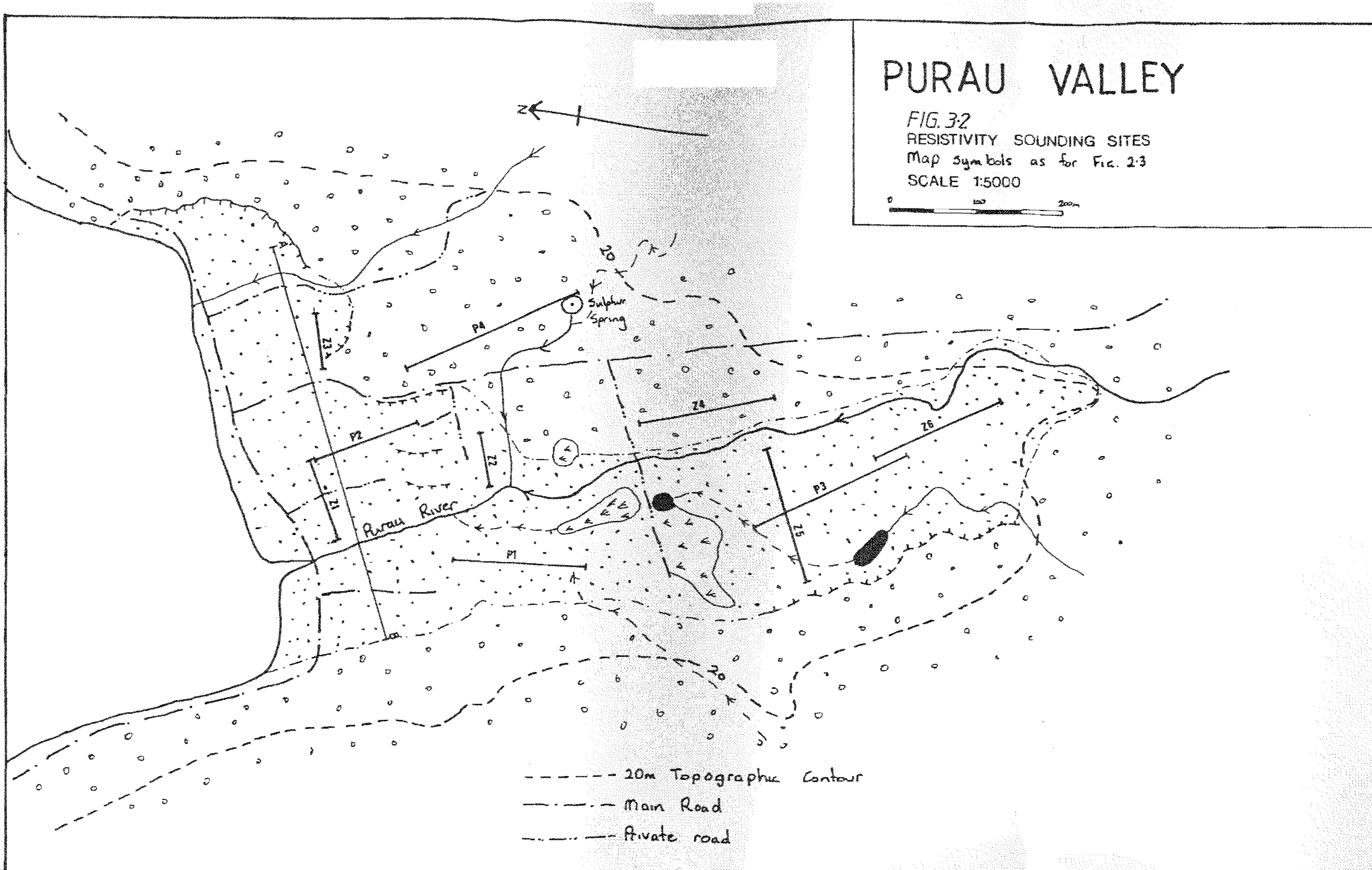
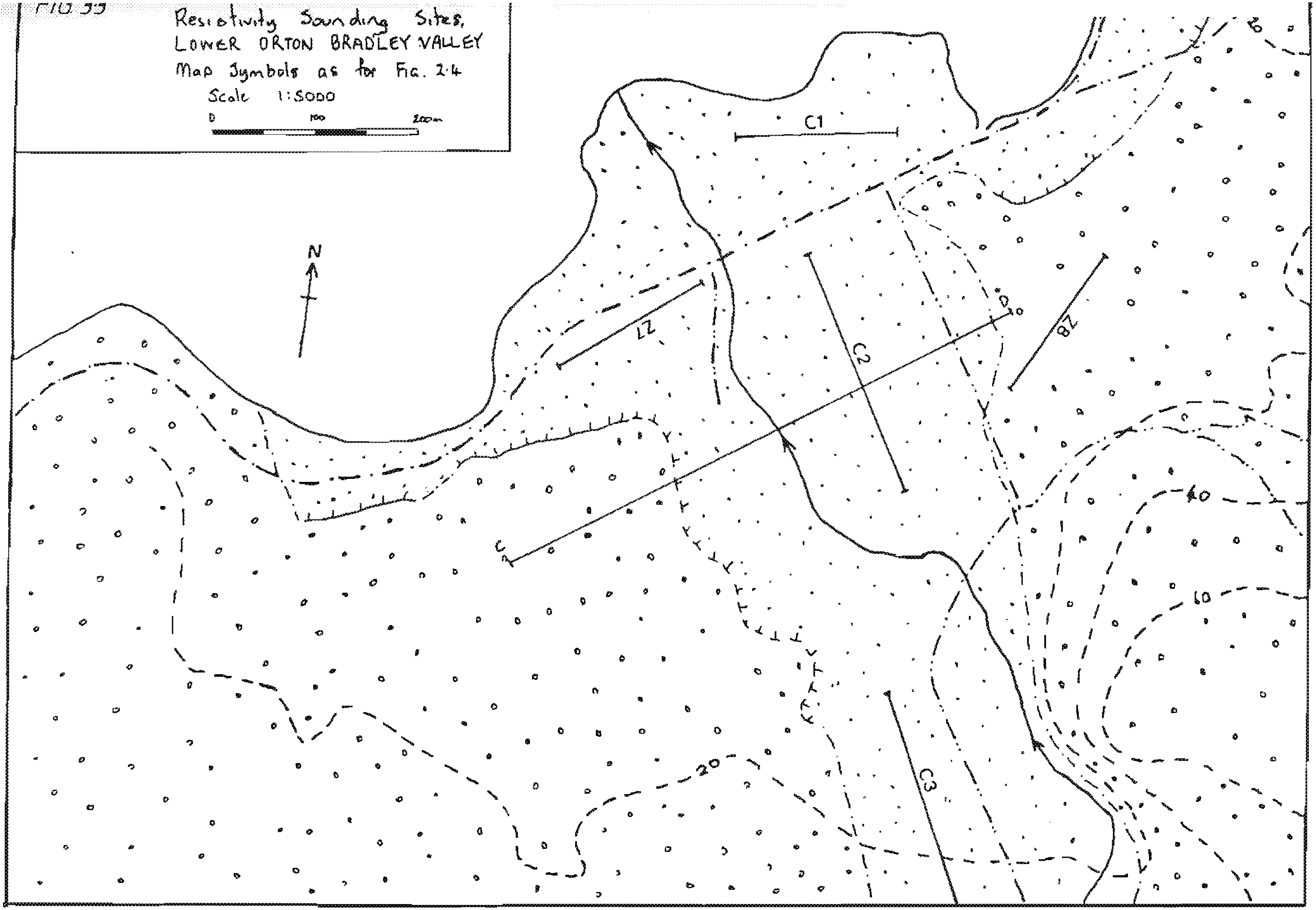

PURAU VALLEY
FIG. 3·2
RESISTIVITY SOUNDING SITES
Map symbols as for Fig. 2·3
SCALE 1:5000
0
100
200m
N
20
Sulphur Spring
P4
Z3
P2
Z2
Z1
Purau River
P1
Z4
Z6
P3
Z5
20
20m Topographic Contour
Main Road
Private road

FIG 3.3 Resistivity Sounding Sites, LOWER ORTON BRADLEY VALLEY
Map Symbols as for Fig. 2.4
Scale 1:5000



Geophysics Division ABEM SAS 300 Terrameter resistivity meter. The maximum spacing between current electrodes (AB) varied between 64 and 250m depending on local conditions, there being limited sounding sites because of dwellings in the lower valley areas. Curve smoothing was carried out according to the method described in White (1985) to produce equivalent Schlumberger resistivities for each sounding.

Represented in Figure 3.4 is a contoured plot of apparent resistivity varying with AB/2 values. The pseudosection shown has a linear depth scale (AB/2) to highlight information on the deeper layers in the valley. Figure 3.4 draws attention to any lateral resistivity changes that may exist, and to any anomalous measurements caused by instrument malfunction or cultural contamination, such as buried wires etc. These sections also reveal whether resistivity changes conincide with changes in topography. No anomalous measurements were observed.

The resistivity of particular type of rock can vary from place to place due to factors such as pore water resistivity and clay mineral content. To aid interpretation the Apparent Formation Factor (AFF) was used as a more diagnostic feature of a particular rock type than its resistivity. The Apparent Formation Facter is defined as the ratio of the resistivity of the saturated rock (bulk resisitiviy) to the pore water resistivity. Measurments of pore water resistivity were calculated for three Purau Valley wells to determine AFF's for the sediments of this valley.

b) <u>Data Analysis Constraints</u>

An understanding of the limitations inherent with the resistivity technique will help avoid making inaccurate interpretations. The following is a brief discussion of some limitations of resistivity data that were considered in the course of interpreting data from this study.

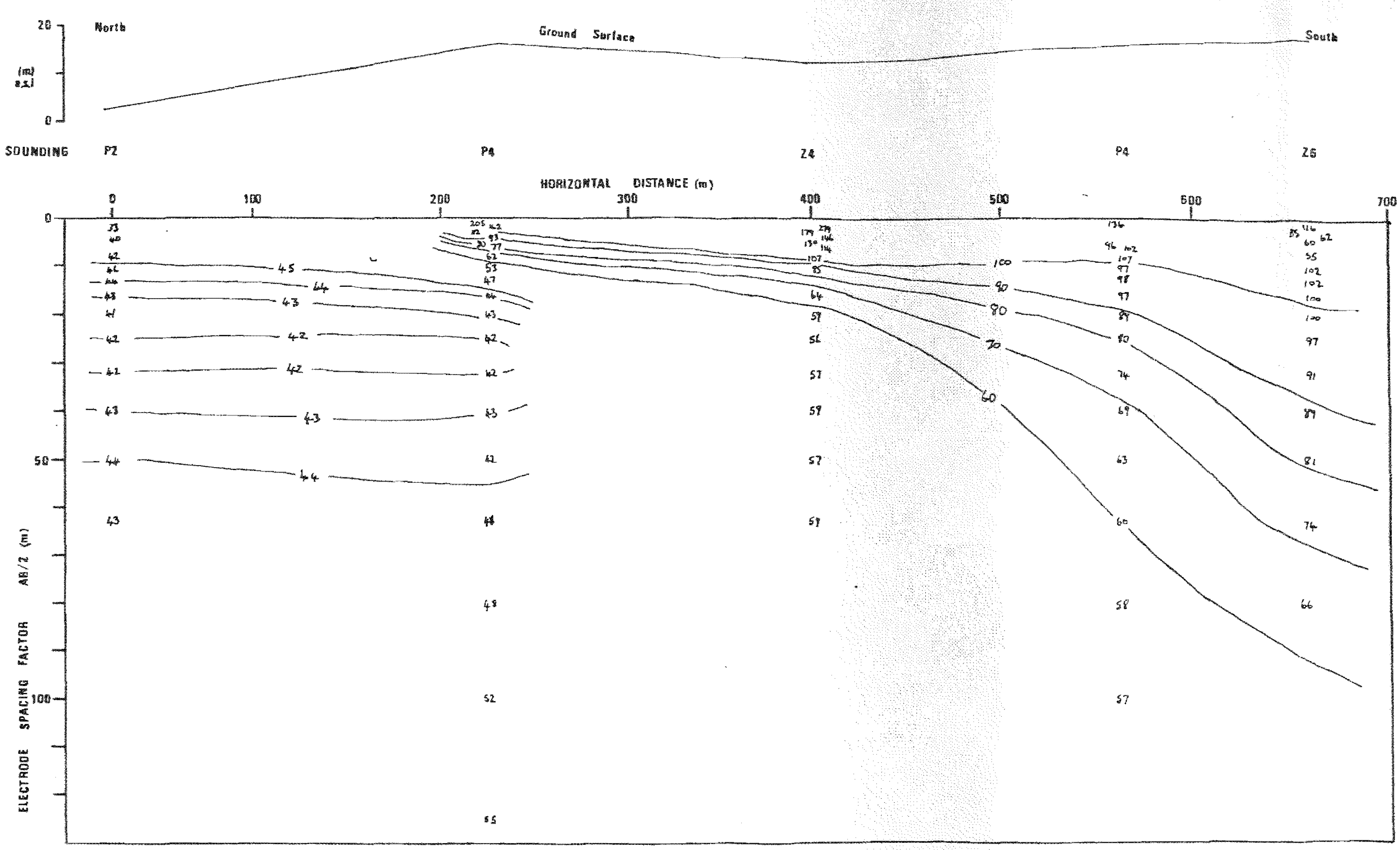


Fig. 3.4 APPARENT RESISTIVITY PSEUDOSECTION PURAU VALLEY

1) The apparent resistivity data for each sounding has been interpreted on the assumption that the sounding was conducted on a flat horizontal surface made up of horizontal layers, each of which is composed of electrically homogeneous isotropic material. In small valleys where a number of depositional environments may be represented (in the case of Purau Valley, for example, valley slope deposits can be found adjacent to marine and alluvial deposits) this assumption is not strictly valid. No marked changes in lateral resistivities were detected in either the Purau or Orton Bradley Valleys.

2) The geolectric section gained may not necessarily represent real changes in lithology because the interpretation process may divide some lithologies into more than one unit, or it could place boundaries that do not coincide with real lithological changes. As an example, a single lithological unit may have variations in pore water chemistry with depth which could give rise to a geoelectric interpretation which divides a single lithologic unit into several layers.

3) The layered ground indicated by the interpretation process in not the only ground that could give rise to the observed apparent resistivites because the interpretation process does not give a unique solution. To aid arriving at useful conclusions all geological information available has to be considered. In this case two logged wells, a number of auger holes and surface geological information was available to assist interpretations for the Purau Valley site. There were no well logs available for the Orton Bradley site but useful comparisions could be made with the Purau Valley site to aid the interpretation process.

3.3.2 Purau Valley Data Interpretation

The range of interpretated resistivity values obtained (388 ohm m to 3 ohm m) for Purau Valley is considered to be very small and if the values for the top metre or so of material are ignored the range is 184 ohm m to 21 ohm m. The top 1m of material was considered to be hydrogeologically irrelevant. The small range of values has made interpretation difficult because the contrast between the resistivities of different lithologies is not great.

a) Volcanic Bedrock Interpretation

On the basis of known depth to volcanic bedrock in two drill holes the bedrock profile was able to be fixed in most locations (Figs. 2.9 and 2.10). The volcanic bedrock in Purau Valley had deduced resistivity values of 107 ohm m to 32 ohm m. Other authors have obtained different ranges for Banks Peninsula Volcanics: for example in Kaituna Valley Namjou (1988) obtained a range of 92 to 42 ohm m for Lyttelton and Mt Herbert Volcanics whilst Simpson (1987) obtained a range of 433 to 29 ohm m for Lyttelton Volcanics. The variation in resistivity values for volcanic bedrock is accounted for by the different types of volcanic product (eg massive lava flows, jointed saturated lava flows, and pyroclastic materials), the degree of weathering and the water content and chemistry of the volcanic materials.

The Purau Valley sediments rest on Lyttelton and Church Volcanics, while the sediments in the Orton Bradley Valley rest on pre-Lyttelton rocks. The depth to volcanic bedrock was found to vary between approximately 6 and 11 metres and is at its greatest at sounding site P2 (Figs. 3.3 and 3.5).

b) Lower Purau Valley Sediments

Figures 3.4 and 3.5 indicate that the sediments filling the lower Purau Valley are geoelectrically different from those that fill the upper valley. Fine grained sediments in the lower valley have resistivities within the range 30 to 40 ohm m, while those fine grained sediments of the upper valley have a range of 30 to 118 ohm m (Fig. 3.5). The top metre or so of surface materials are excluded because they are hydrogeologically not significant and geoelectrically highly variable.

The lower Purau Valley sediments that immediately overlie volcanic bedrock consist of yellow-brown sandy clayey silts with some boulders, sandy fine gravels and blue silty clays. They have resistivities in the range 38 to 21 ohm m (Fig. 3.5). Sounding P2 is assumed to approximately overlie the position of a layer of sandy fine gravels referred to as the Lower Purau Aquifer (Fig. 3.3). An alternate computer model was produced for sounding P2 with an additional layer added overlying volcanic bedrock, the purpose of this exercise being to determine if this layer could be defined by the resistivity method. The layer was given a resistivity of 65 ohm m (the value gained for other gravels found in Purau Valley) and given a thickness of 4m (the approximate known Lower Aquifer thickness in this area found from borehole logs). A plot of the expected field apparent resistivities using the ammended model for site P2 is given in (Fig. 3.6). The computer simulation is drawn with the field data and shows that the two curves are not significantly different. This is interpreted to indicate that it would not be possible to delineate the Lower Purau Valley Aquifer using the resistivity method at site P2.

A second gravel layer is interpreted to overlie the lower Purau Valley sediments discussed so far, known as the Upper Purau Valley Aquifer (Figs. 2.9 and 3.5). Resistivities for this layer vary between 120 and 16 ohm, m

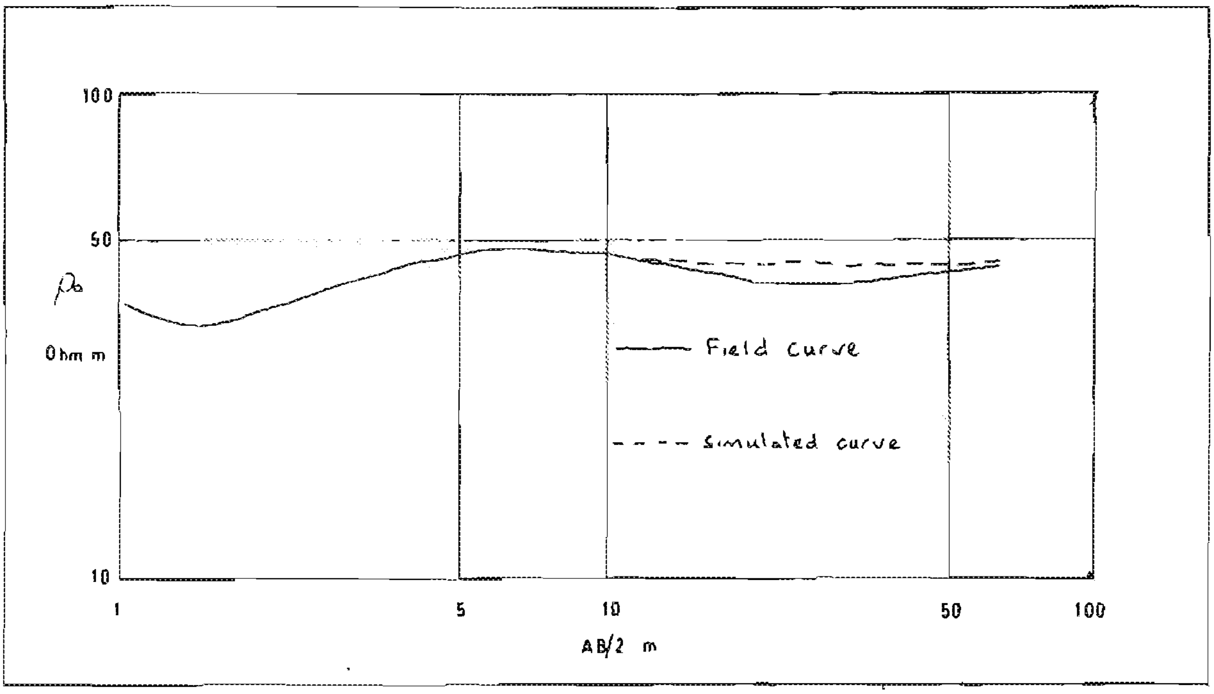


Fig. 3.6 Plot of measured apparent resistivities for sounding P2 and a simulated model for sounding P2 with an extra layer added at depth 8.8 to 12.9m, with a resistivity of 65 ohm m.

and its thickness between approximately 2 and 5m. This gravel layer is interpreted to only be present north of M36 GR 900297 (Fig. 2.2), and is found as a laterally extensive layer which covers the width of the alluvial plain. The lowest resistivity value of 16 ohm m for this gravel was found adjacent to the coast, site Z1, and probably represents sea incursion. Generally resisitivity values of approximately 65 ohm m were typical of this gravel.

c) Upper Purau Valley Sediments

With the exclusion of the upper metre or so of materials the upper Purau Valley sediments consist of light to dark brown and bluish grey silty clays with some sands and gravels. These sediments have resisitivity values in the range 118 to 99 ohm m (Figs. 3.3 and 3.5), occur as a laterally extensive layer of approximately 10 metres thickness and up to 200m in width.

d) Formation Factors

The Apparent Formation Factor (AFF) for a given layer is defined as the ratio of the resistivity of the saturated rock (bulk resistivity) to the pore water resistivity and values for the Upper Purau Aquifer range between 3.5 and 3.65, and between 1.27 and 2.29 for the fine grained sediments found in the lower Purau Valley. If a resistivity of about 55 to 65 ohm m is assumed for the Lower Purau Aquifer then Apparent Formation Factors vary between 4.02 and 4.12 for this gravel.

Jackson et. al. (1978) has established a relationship between Apparent Formation Factors and porosity in marine sands which is widely used in resistivity investigations. If the assumption is made that there is no matrix conduction in both Purau gravel units (that is, they are essentially free of clay materials) then the following porosity values are obtained from Fig. 3.7; for the Upper Purau Aquifer a porosity of 38 to 46% and for the Lower Purau Aquifer a

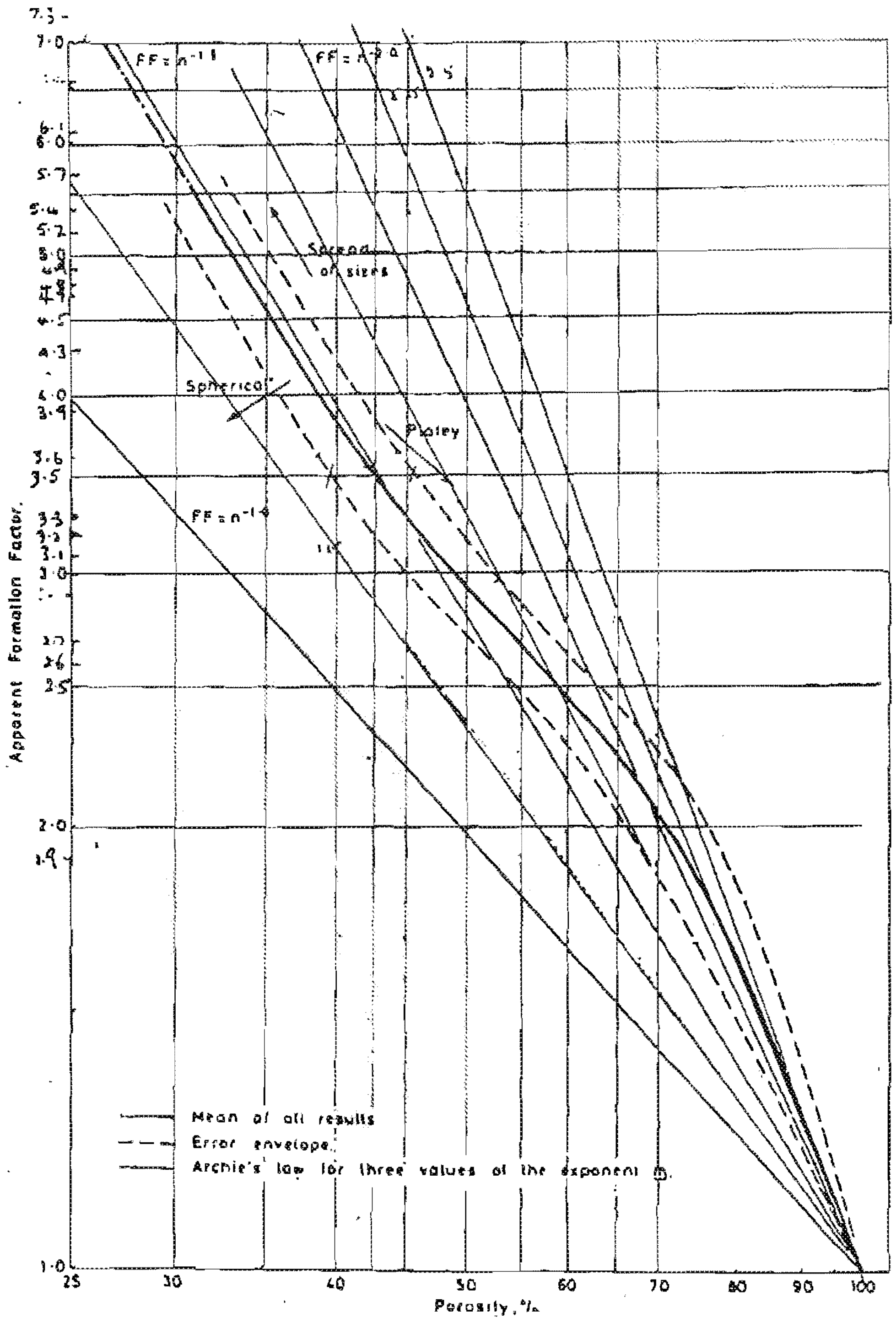


Fig. 3.7 Formation factor verus porosity, with the dashed lines representing an error envelope, and the solid line the mean of all Jackson's data. (From Jackson et al, 1978)

porosity of 36 to 42%. For the Lower Aquifer a value of 65 ohm m has been used to approximate the bulk resistivity of this layer.

Jackson's results tend to overestimate porosity by around 3 to 5% (M. Broadbent, pers. com.), and an approximate laboratory determination of the porosity of the Upper and Lower Aquifer gravels was also carried out by filling a known volume with a sample of the sandy gravel. The container was then filled with water, and porosity was calculated according to the following relationship; porosity = void space volume/volume of material. As the real packing of either of these gravels can not be exactly simulated in the laboratory the porosity values gained are assumed to be approximate only. Approximate porosity values were found to be 33% for the Upper Aquifer gravel and 43% for the Lower Aquifer gravel. The laboratory porosity of 33% for the Upper Aquifer is consistant with the expected value from Jackson et. al. (1978) ,taking in to consideration the overestimation, however, the value of 43% for the Lower Aquifer is outside the range determined from Jackson et. al. (1978). A possible explanation for this is that the resistivity value used for the Lower Aquifer was only an estimate and the real value may be different.

3.3.3 Orton Bradley Valley Data Interpretation

No drill hole information was available to assist in interpreting resistivity data from the Orton Bradley Valley, and interpretation of the resistivity data from this valley was therefore based on the results gained from the Purau Valley investigation (Figs. 3.2 and 3.8). Similar processes are assumed to have contributed to the formation of this valley and its subsequent infilling.

Excluding the top metre or so of sediments, the range of resistivities values obtained for the Orton Bradley Valley were higher than those found in Purau Valley, being 730 to 6 ohm m.

a) Volcanic Bedrock Interpretation

The range of resistivity values that are interpreted to represent volcanic bedrock in the Orton Bradley Valley vary between 86 and 6 ohm m. Only two sites are interpreted to show clearly the depth to bedrock, where at site C1 the depth to bedrock is about 5m and at site C3 depth to bedrock is about 3m. At those sites where depth to bedrock could not be determined (sites C2 and Z8) the resistivity of the sediments and volcanic bedrock was assummed to be about the same and hence no resistivity contrast existed.

b) The Orton Bradley Valley Sediments

Interpretation of Fig. 3.8 data at the most inland site C3 (Fig. 3.2) indicates that only low resistivity clays and silts overlie volcanic bedrock. The same material is interpreted to overlie bedrock at site C2. Overlying these fine sediments at site C2 and Z7 is a high resistivity layer (709 to 730 ohm m) interpreted to represent a gravel layer of between 1 and 3m thickness. This gravel layer is not laterally extensive and thickens to its maximum at site C1 (Figs. 3.2 and 3.8). The gravel layer is not present up valley of the old homestead site, M36 GR 863279. The resistivity of this gravel decreases coastward (279 ohm m at site C1) probably indicating an increase in pore water content and pore water salinity. At site C1 the gravel is intrepreted to immediately overlie bedrock. Site C1 is interpreted to have a low resistivity, 41 ohm m, layer of sandy clays and silts overlying the higher resistivity gravel layer of approximately 1.5m thickness (Fig. 3.8).

At site Z8 a considerable thickness (>6m) of low resistivity (66 to 20 ohm m) clays and silts are found. Interpretation of the data from this site did not indicate any high resistivity layers and the high resistivity gravel layer found at sites C1, C2, and Z7 is probably not present.

c) Formation Factors

No water conductivities were taken from the Orton Bradley Valley. The resistivity survey is interpreted to show that there is only a small thickness of alluvial sediments (<6m) and therefore any groundwater resource found within these sediments will be limited (Fig. 2.4).

3.4 HYDRAULIC MODELLING

3.4.1 Data Collection and Analysis

A constant rate pumping test was carried out at the Purau Motor Camp to determine the hydraulic parameters of the Lower Purau Aquifer. A newly drilled 150mm bore was used as the pumping bore and a single observation bore was located 10m from the pumped bore. The observation bore is a 50mm driven well put down several years ago and has been in constant since then to supply the Purau Motor Camp. Geophysical logging of the observation piezometer (old Motor Camp well, well 14) indicates this well penetrates the upper 0.8m of the Lower Purau Aquifer. The new Motor Camp well (well 13) penetrates the full 4.55m thickness of the Lower Purau Aquifer. As the lower 0.77m of the aquifer is clay-bound, the effective thickness of the aquifer is 3.78m.

The nearest septic tank is 30m from both wells and meets the requirement of the NCCB that any well used for a domestic supply must be a minimum of 30m from any septic tank.

3.4.2 Pump Test Results for the Lower Purau Aquifer

A trial pumping of the aquifer the day before the test was carried out to determine the appropriate pumping rate, and it was found pumping at 30 litres/minute would produce the required drawdown rate that would make the curve matching interpretation process accurate. It was also necessary to determine this figure so that dewatering of the aquifer did not occur during the pumping test. If the aquifer was dewatered during the test this would have altered some of the parameters in the Theis equation and made interpretation difficult.

Drawdown measurements were taken over a period of 231 minutes and recovery measurements over a period of 180 minutes. It had been intended to pump for 240 minutes, but equipment failure prevented this.

The Theis method of analysis was used for this test. Analysis of a plot of drawdown/time and a Theis theoretical curve in the normal manner (Fig. 3.9) shows that the field data departs from the theoretical curve approximately nine minutes after pumping began. Drawdown is clearly greater than would be expected in an aquifer of semi-infinite lateral extent, and suggested that the aquifer was a bounded system of finite extent.

A transmissivity of $11.92m^2$/day and storage co-efficient of 3.87×10^{-4} were calculated for the lower Purau Aquifer. This low transmissivity indicates that this well cannot sustain high pumping rates for any length of time otherwise the aquifer will be dewatered very quickly. For sustained pumping it appears that a rate of between 27 and 38 litres/minute is appropriate.

3.4.3 Boundary Configuration for the Lower Purau Aquifer

When an aquifer is recognised as having finite dimensions, direct analysis of the test data by standard methods may not be possible (Kruseman, et. al., 1970). The methods of images can be used to duplicate hydraulically the effects on the flow regime system, and is the equivalent to removing a physical entity and substituting a hydraulic entity (Figs. 3.10 and 3.11). The finite flow system is

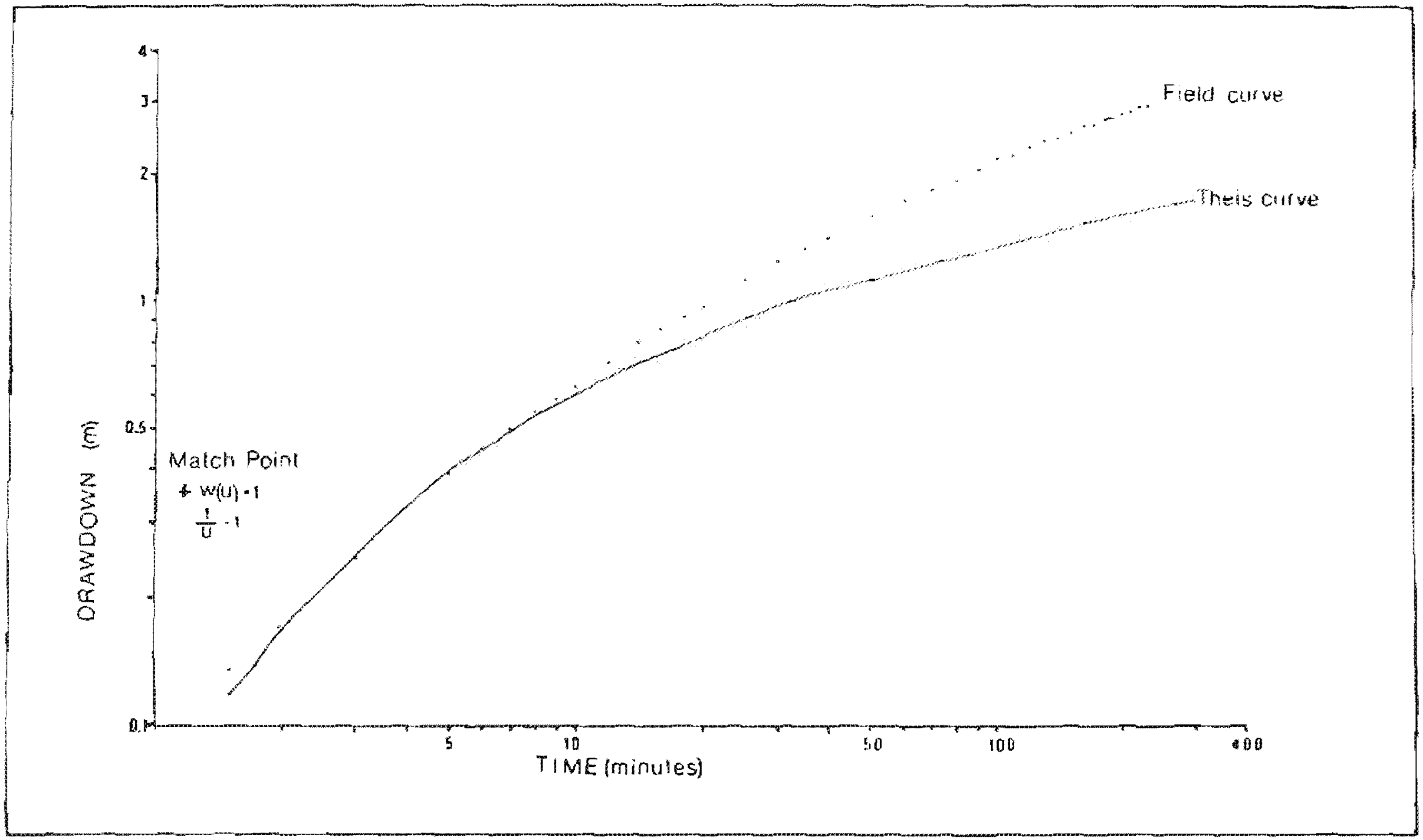


Fig. 3.9 Plot of measured drawdown with a Theis theoretical curve.

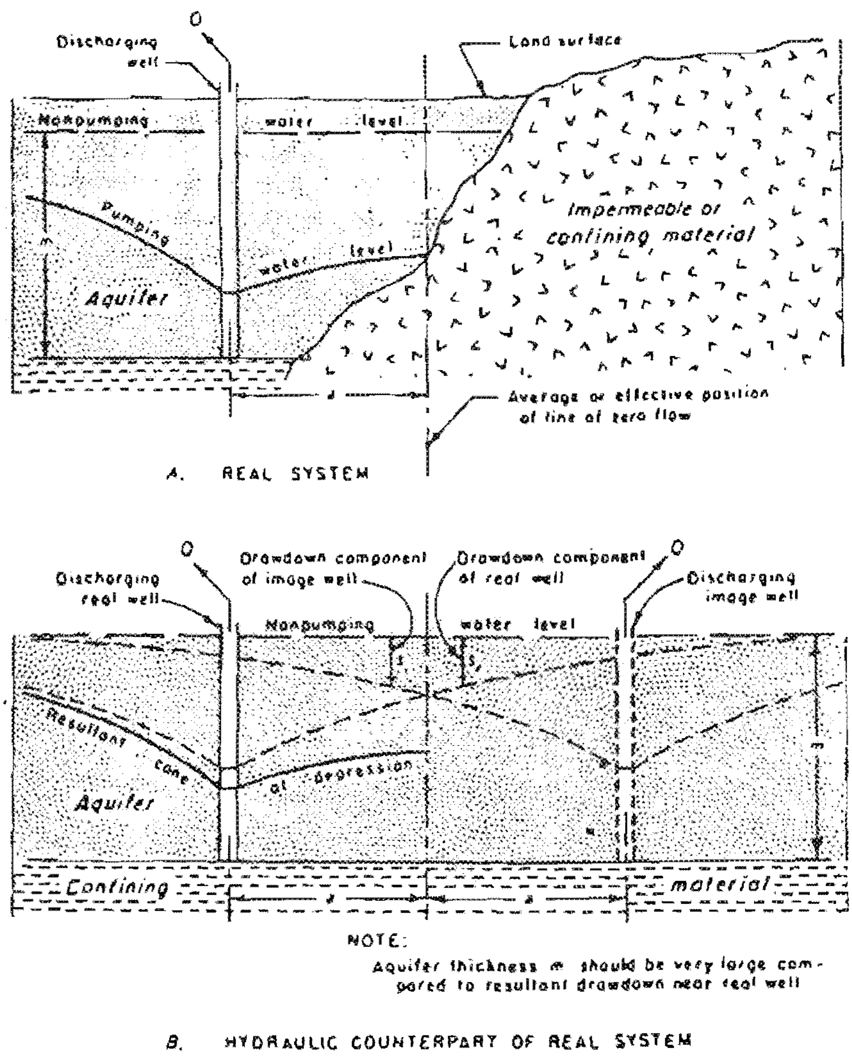


Fig. 3.10 Idealised section views of a discharging well in a semi-infinite aquifer bounded by an impermeable formation, and of the equivalent hydraulic system in an infinite aquifer. (From Ferris et al, 1962)

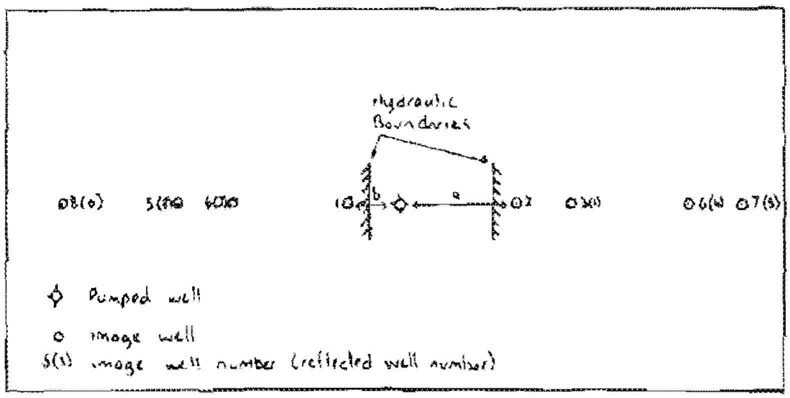


Fig. 3.11 Boundary configuration and location of image wells for a system consisting of two parallel boundaries. (After Kruseman and De Ridder, 1970)

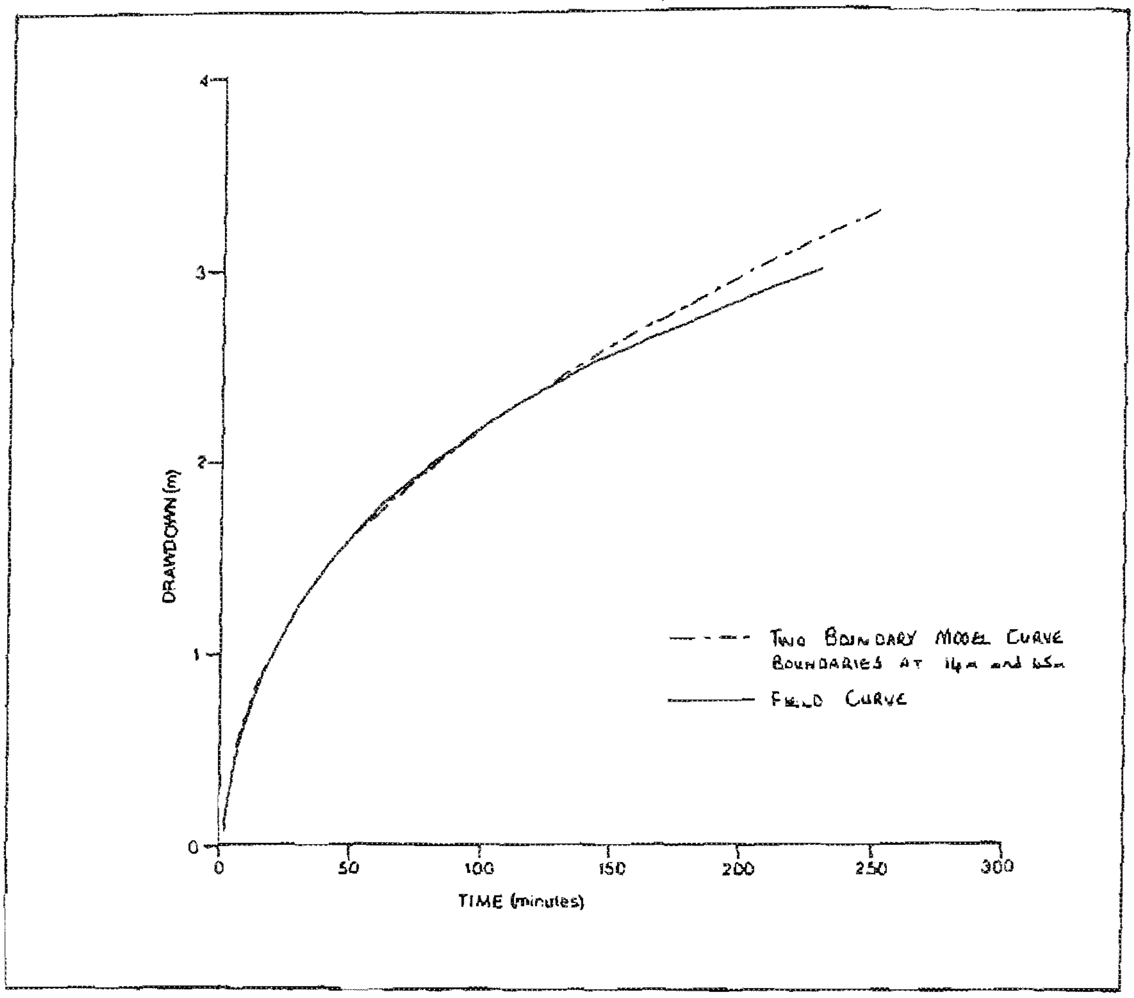
thereby transformed by substitution into one involving an aquifer of infinite areal extent.

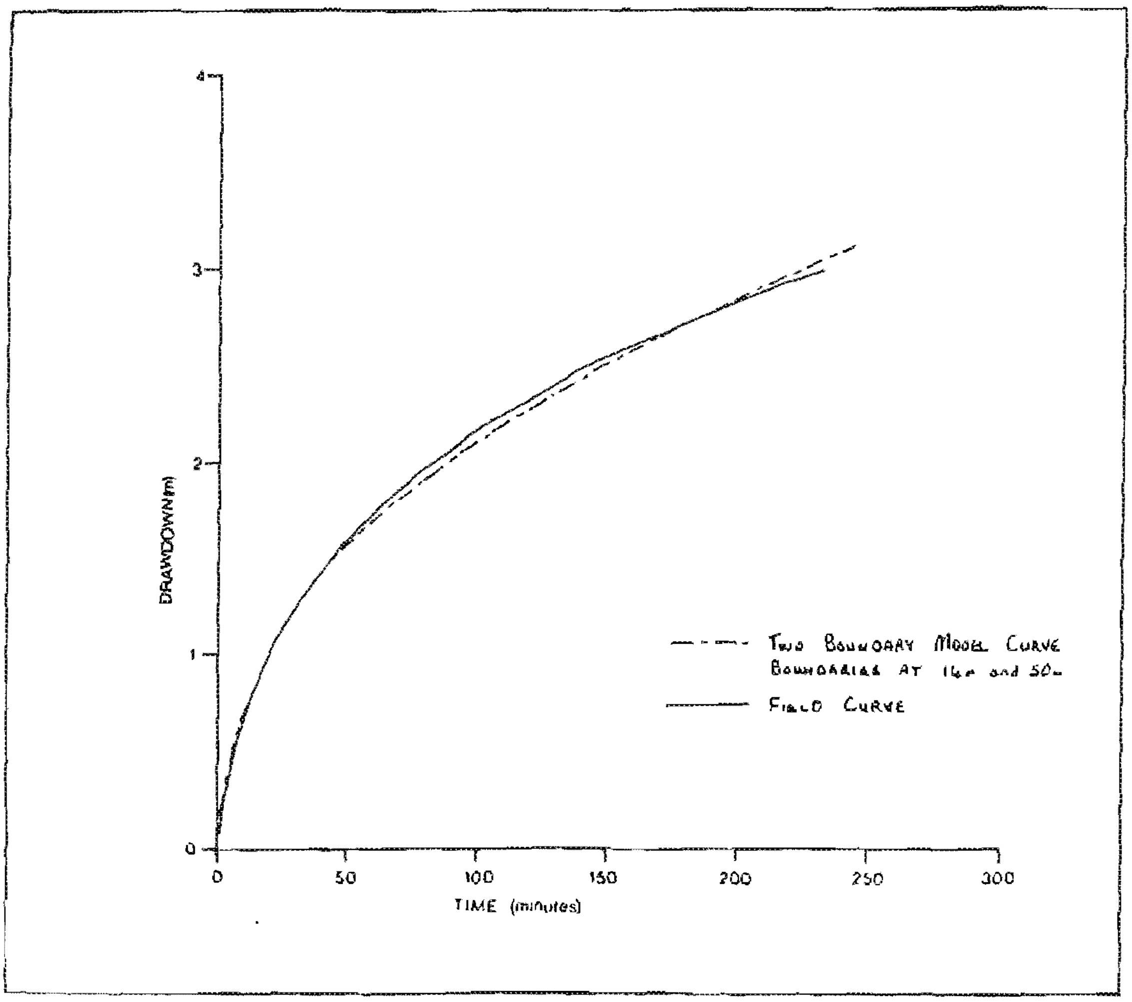
Although most geologic boundaries do not occur as abrupt discontinuities, it is often possible to treat them as such hydraulically. It is assumed that an irregularly sloping boundary can, for practical purposes, be replaced by a vertical boundary without sensibly changing the nature of the problem. The hydraulic condition imposed by the vertical boundary is that there can be no groundwater flow across it, for the impermeable material cannot contribute water to the pumped well.

Stallmans method (Appendix Five) was used to determine the location of the hydraulic boundaries for the Lower Purau Aquifer. A one-boundary computer simulation located the first boundary at approximately 14m from the pumped well, and a second two-boundary computer simulation fixed the second boundary at 50m from the pumped well (Figs. 3.12 and 3.13).

The writer does not wish to imply that both boundaries are exactly 14m and 50m from the pumped well, but using this form of simulation it has been possible to approximate the position of these two boundaries which will assist in locating future drilling sites. This analysis also does not define the relative positions of each boundary with respect to the pumped well. However, geological information suggests that the 14m boundary is east of the pumped well and the 50m boundary west of the pumped well (Fig. 3.3).

Pump test modelling techniques have thus helped to identify the Lower Purau Aquifer as a strip aquifer of approximately 64m width.





Figs. 3.12 and 3.13 Drawdown plots of field data and simulated data showing two separate boundary configurations.

3.4.4 Piezometric survey of the Purau Valley

a) Data collection

Water levels in 12 bores located in Purau valley were monitored over a period of 10 months, usually on a fortnightly basis, to gain an understanding of the direction of groundwater movement, and hence groundwater discharge and recharge patterns. Appendix Ten includes well water level data for the period October 1987 to July 1988, and the analysis of the piezometric contours. Analysis was limited to wells that penetrate the Lower Purau Aquifer. Those wells that penetrate the Upper Purau Aquifer are found to only extend about 150m or so from the coast and it was found that the piezometric gradient was virtually nil over this distance.

b) Piezometric Contour Analysis

The distribution of piezometric head for the Lower Purau aquifer is shown in Fig. 3.14 and shows that there is a very low hydraulic gradient towards the coast in both winter and summer. The hydraulic gradient is at its lowest in the summer months, and care will need to be taken so that groundwater extraction levels do not lower this gradient to the point where sea water intrusion can occur.

Based on a transmisivity of 11.92 m^2/day, a width of approximately 64m (calculated from pumping test results) and an approximate hydraulic gradient of 0.01, flow through the Lower Purau Aquifer can be calculated from the following relationship:

$Q = TIw$ where, Q = Flow (m^3/day)
T = Transmissivity (m^2/day)
I = Hydraulic gradient
w = aquifer width (m)

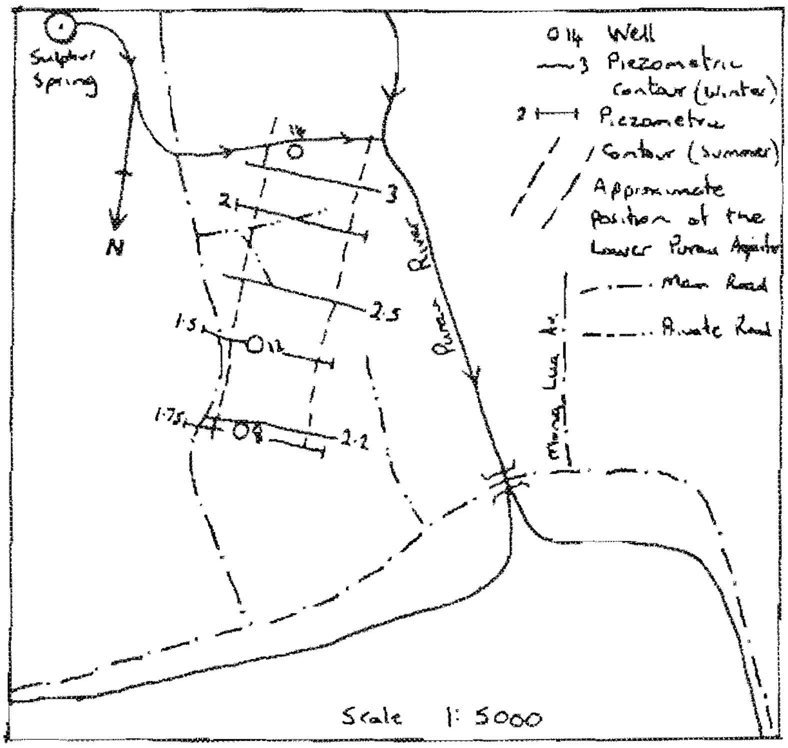


Fig. 3.14 Piezometric contours for the Lower Purau Aquifer.

Flow (Q) was found to be 7.6 m^3/day, and such a low flow is a reflection of the small interpreted volume of the aquifer, the low hydraulic gradient found to exist in this aquifer and the low rate of recharge interpreted to occur to this aquifer.

3.5 HYDROGEOLOGIC MODELS

3.5.1 Purau Aquifer Systems

Two alluvial aquifers have been found in the lower Purau Valley (Fig. 3.15). Drill hole information has revealed a 3.78m thick, water-bearing, sandy gravel layer immediately overlying volcanic bedrock in well 13 (Figs. 2.3 and 2.9), and this is referred to as the Lower Purau Aquifer. Resistivity surveys have failed to identify this aquifer for the reasons outlined in section 3.3.2. A second drill hole (well 11, Figs. 2.3 and 2.9) has revealed the same lithologic units in the same stratigraphic sucession as found in well 13. The only difference in stratigraphy between these two drill holes is that a brown clayey silt unit, found in well 12, is correlated with the sandy gravel found in well 13 (Fig. 2.9). These two lithologies are interpreted to represent facies equivalents, deposited in a fluvial environment. The sandy gravels are interpreted to represent infilled river channels and the clayey silts represent overbank mud flood deposits.

There may be more than one infilled river channel within this sequence, however only one channel has been located and hydraulic information indicates that it is approximately 64m in width (Section 3.4).

Overlying and confining the alluvial sequence is a silty clay layer that is interpreted to represent a marine/estuarine unit deposited as a result of sea level fluctuations in the late (c. 6000 years BP) Pleistocene

(Fig. 3.15). Sea levels appear to have fluctuated no more than 1 to 2m (D H Bell, pers. com.) within the past 6000 years.

A lowering of sea level or tectonic elevation of the Peninsula has allowed a second more laterally extensive gravel layer (interpreted to represent river deposited alluvium), and referred to as the Upper (unconfined) Purau Aquifer, overlies the marine/estuarine muds. Nine of the 14 wells in the Purau valley draw water from this gravel, which seems to only be water-bearing in some locations. Although wells 11 through 14 penetrate this aquifer it was found to be dry at these locations. River deposited silts overlie the Upper Purau Aquifer and complete the geologic succession in the Purau Valley (Fig. 3.15). There has been no datable material recovered from either the Purau or Orton Bradley Valleys to confirm these conclusions.

3.5.2 Orton Bradley Aquifer Systems

Interpretation of the alluvial sediments found in the Orton Bradley Valley is based on the geological information gained from the Purau Valley. Resistivity data suggests there is a narrow, thin (<3m) gravel layer within the alluvial sediments of this valley. Resistivity values decrease towards the coast suggesting, this aquifer is similar to the upper Purau in that it is only water-bearing near the coast (Fig. 2.2, 3.8 and 3.16).

The small lateral extent (about 400m in width) of this aquifer suggests it will not provide significant quantities of groundwater.

3.6 HYDROCHEMICAL STUDIES OF ALLUVIAL GROUNDWATER

3.6.1 Test Programme and Background Theory

Hydrochemical studies were undertaken in order to gain a better understanding of the recharge sources, groundwater

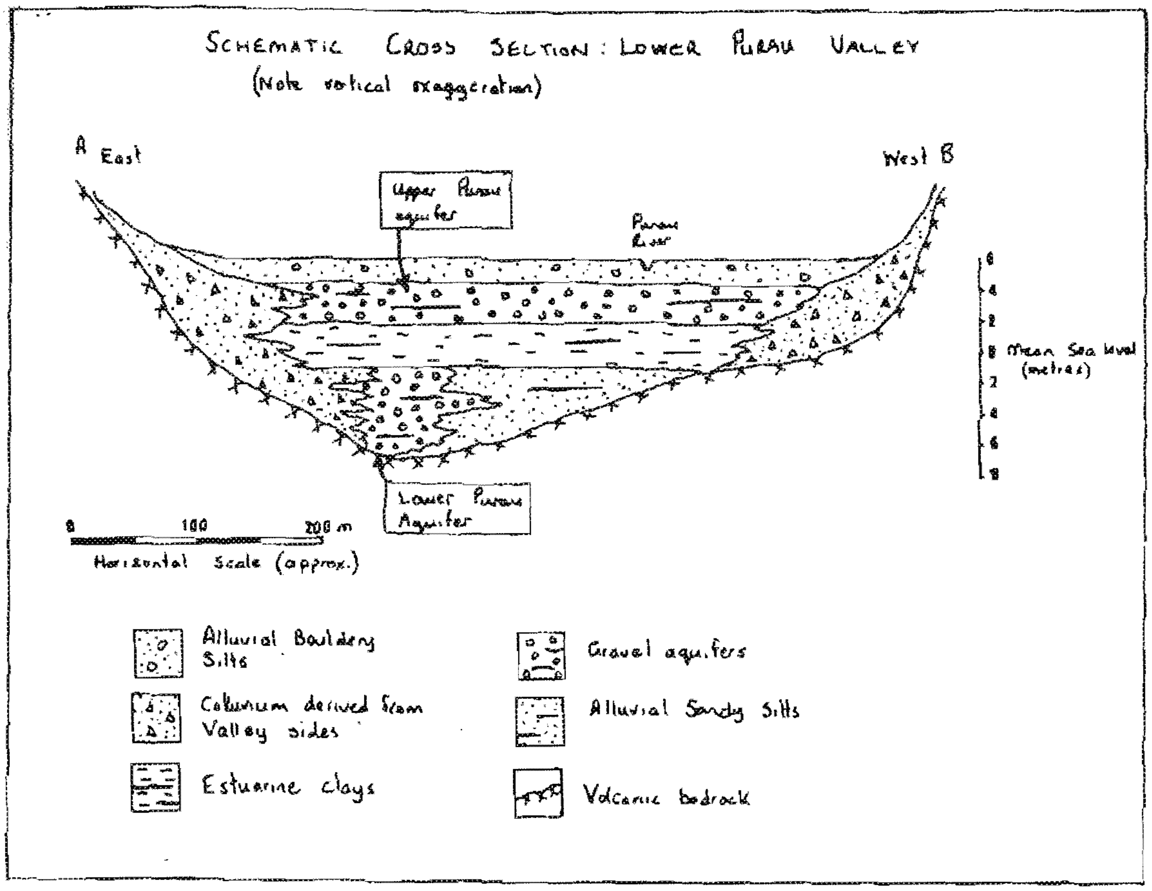


Fig. 3.15 Schematic cross section of the Lower Purau Valley.
(see Fig. 3.2 for cross section location)

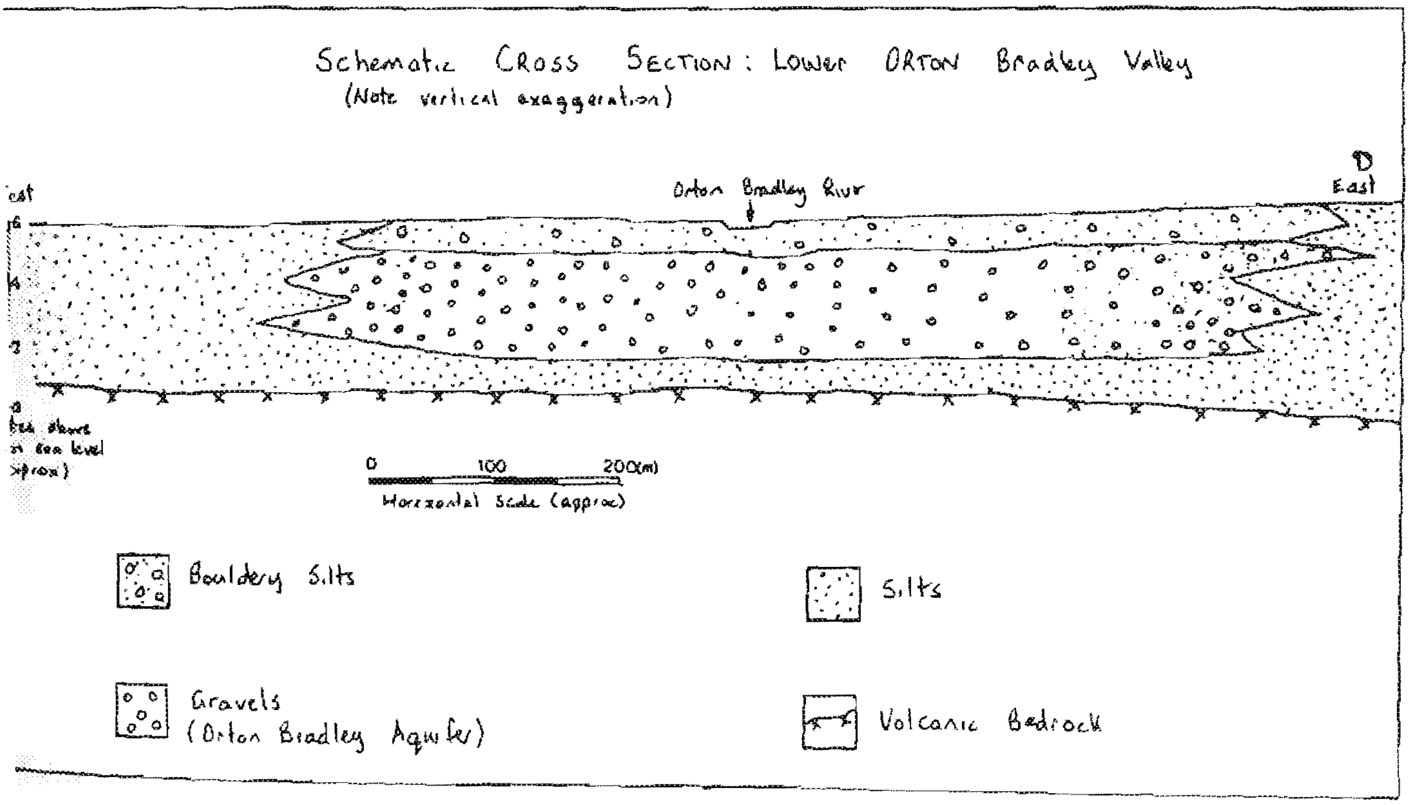


Fig. 3.16 Schematic cross section of the Lower Orton Bradley Valley.
(see Fig. 3.3 for cross section location)

residence times, water quality and the origins of various elements found in the valley floor aquifer systems. Two samples from the alluvial aquifers of Purau Valley are discussed in this section (Fig. 3.17 and Table 3.1). Two further analyses of the deeper groundwater found in the Diamond Harbour area and their relationship to the alluvial groundwater will be discussed later in the Chapter. All chemical analyses were carried out by DSIR Chemistry Division (Ilam) and those discussed here were from the following sources:

1) Purau Motor Camp well 13 (M36 GR 899296) DSIR sample R2445/1

2) J. Fowler well 9 (M36 GR 900298) DSIR sample 2445/5

Many of the minerals present in volcanic rocks are thermodynamically unstable and tend to slowly dissolve when in contact with water, especially CO_2-enriched water. The dissolution processes cause the water to acquire dissolved constituents, and the rock to become altered mineralogicaly.

When chemically aggressive CO_2-charged waters low in dissolved solids encounter silicate minerals high in concentrations of cations, aluminium and silica, the cations and silica are leached, leaving an alluminosilicate residue with increased Al/Si ratio. The residue is usually a clay mineral such as kaolinite or illite. The cations released to groundwater are normally Fe^+, Na^+, K^+, Mg^{2+} and Ca^{2+}. Another consequence of this process is a rise in pH and HCO_3^- concentration (Freeze and Cherry, 1979).

Groundwaters contained in volcanic rock reservoirs are usually more effective solvents owing to the slower movement of the water and the more intimate contact between water and rock minerals.

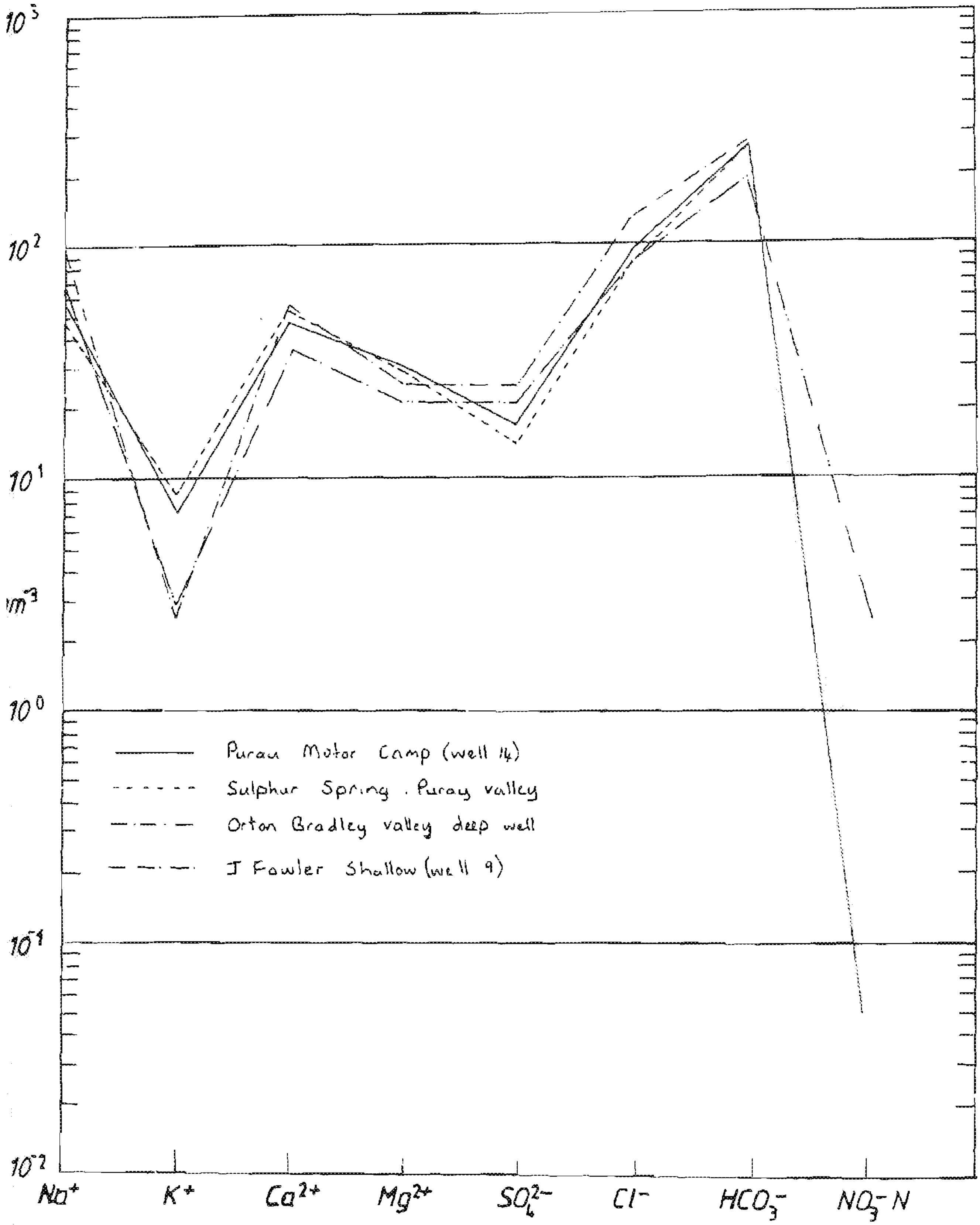


Fig. 3.17 Chemical profiles of the alluvial groundwaters of the Purau Valley with profiles of the deep circulating groundwaters for comparison.

Table 3.1 Chemical Analyses of Purau Valley Alluvial Groundwaters

Sample No.:	R2445/1 (Well 13)	R2445/5 (Well 9)
ANALYSIS		
Units g/m^3, except pH or unless otherwise stated.		
pH	7.3#	6.7##
pH after aeration	8.1	8.3
Acidity to pH 8.3 (as CO_2)	18	43
Total Alkalinity to pH4.5 as HCO_3	260	190
Alkalinity to pH 8.3 (as CO_3)	NIL	NIL
Turbidity (NTU)	9.6**	1.0
Colour (from Absorbance 270nm) TCU	1	2
Absorbance units (270nm, 1cm cell)	0.011	0.017
Chemical Oxygen Demand (as O)	LT4	LT4
Ammoniacal Nitrogen	0.11	LT0.04
Nitrite Nitrogen	LT0.005	0.029
Nitrate Nitrogen	LT 0.05	2.5
Soluble Phospate (as P)	LT0.06	LT0.06
Sulphate	17	21
Bromide	0.35	0.34
Chloride	95	86
Fluoride	0.22	0.29
Calcium	47	35
Magnesium	31	21
Potassium	7.2	1.7
Sodium	56	67
Reactive Silica (as SiO_2)	60	40
Reactive Aluminium	LT0.04	LT0.04
Arsenic	LT 0.01	LT0.01
Antimony	LT0.01	LT0.01
Boron	LT0.2	LT0.2
Cadium	LT0.005	LT0.005
Chromium	LT0.02	LT0.02
Copper	LT0.02	LT0.02
Iron	2.2**	0.94*
Lead	LT0.05	LT0.05
Lithium	LT0.01	LT0.01
Manganese	0.38*	0.32*
Nickel	LT0.05	LT0.05
Selenium	LT0.005	LT0.005
Strontium	0.25	0.19
Zinc	0.16	1.07
Total Hardness (as $CaCO_3$)	250**	170*
Conductivity at 20 deg C (mS/m)	66	60
Langelier Index at 20 deg C	-0.3	-1.2

Analytical results relate only to the sample as received.
The letters LT in the above table mean "less than".

This sample does not comply with the following NZ Standard Guidelines:
##outside maximum range * exceeds lower guideline limit

3.6.2 Calcium (Ca^{2+}) and Magnesium (Mg^{2+})

a) Calcium

The concentration of calcium in wells 9 and 13 was found to be 35 and 47 g/m^3 respectively (Fig. 3.17 and Table 3.1). The origin of these high concentrations of calcium (compared to most Canterbury Plains groundwater) appears to be from the dissolution of the silicate minerals pyroxene and more importantly plagioclase feldspar, which is one of the most important rock forming minerals in the Diamond Harbour area. Most plagioclase feldspars in the local area tend to be of calcium-rich labradorite composition (see Appendix Eight). Calcium-bearing plagioclase feldspars are less stable in the presence of mildly acidic water when compared to non-calcium bearing feldspars (Hem, 1959). The calcium-rich clinopyroxene, diopside, is also present in rocks in the area and dissolution of this mineral will also yield calcium ions.

In the presence of H^+ calcium carbonate in readily soluble in water.

$$CaCO_3 + H^+ = Ca^{2+} + HCO_3^-$$

As long as a sufficient supply of carbon dioxide is available, calcium and bicarbonate ions are produced in solution. Such a solution can exist in stable form when under pressure sufficient to prevent the escape of carbon dioxide (Hem, 1959).

Hem (1959) also notes from experimental evidence that the solubility of calcium carbonate increases in the presence of sodium and potassium ions. Sodium and potassium are present in these groundwaters in significant concentrations (Table 3.1).

b) Magnesium

The concentration of magnesium in wells 9 and 13 was 21 and 31 g/m^3 respectively (Fig. 3.17 and Table 3.1). The origin of the high concentrations of magnesium (compared to most Canterbury Plains groundwater) in the alluvial groundwater of Purau Valley appears to be the silicate olivine and pyroxene. Olivine is present in phenocryst and groundmass phases in most rocks found in the area, and tends to have high concentrations of the Mg-rich forsterite end member (Appendix Eight).

Mafic rocks rich in minerals like olivine are especially subject to the serpentinization reaction and yield silicia and magnesium carbonate which maybe dissolved in circulating water. Magnesium carbonate, like calcium carbonate is more soluble in the presence of carbon dioxide. For example, the serpentinization of forsterite may proceed as follows (Hem, 1959):

$$\underset{\text{(forsterite)}}{5Mg_2SiO_4} + 4H_2O + 4CO_2 = \underset{\text{(serpentine)}}{2H_4Mg_3Si_2O_9} + 4MgCO_3 + SiO_2$$

Like calcium, magnesium is normally present in ionic form in solution and is also more readily dissolved by water containing sodium salts than by pure water (Hem, 1959).

Calcium/magnesium ratios for wells 9 and 13 were found to be 1.01 and 0.92 respectively. Hem (1959) suggests that low values (about 1) of this ratio may indicate that magnesium silicate minerals are being dissolved, or that in some cases the low ratio may indicate sea-water contamination. The ratio of calcium to magnesium for sea water is about 0.2. The evidence for sea water contamination is at this stage inconclusive, and the writer believes that the origin of the magnesium in these waters is the dissolution of Mg-rich silicate minerals.

3.6.3 Sodium (Na^{+}) and Potassium (K^{+})

a) Sodium

The concentration of sodium in wells 9 and 13 was found to be 67 and 56 g/m^3 respectively (Fig. 3.17 and Table 3.1). A number of sources are postulated for the high sodium concentrations in the alluvial aquifers of Purau Valley.

1) Sodium may occur as part of the terrestrial dust in the precipitation in coastal areas. These amounts of sodium are considered to be very small and insignificant amounts of sodium are assumed to be derived from this source (Matthess, 1982).

2) Sea water contamination of the Purau Aquifers could account for the high concentration of sodium in these waters, but as previously stated there is no evidence to support widespread sea water contamination of either the Upper or Lower Purau Aquifers. Resistivity sounding Z1 (Fig. 3.3) did however, indicate possible sea water contamination of the Upper Purau Aquifer within 100m of the coast (Appendix Three). Other resistivity soundings in the Purau Valley showed no indication of sea water contamination.

3) The most likely source of sodium in these groundwaters would appear to be from the dissolution of feldspars (Hem, 1959). While most plagioclase feldspars found in the area are calcium-rich they also have a minor proportion of sodium within the mineral lattice (Appendix Eight).

b) Potassium

The concentration of potassium in wells 9 and 13 was found to be 1.7 and 7.2 g/m^3 respectively (Fig. 3.17 and Table 3.1). The concentration of potassium in these shallow groundwaters is significantly lower compared to that of sodium. Hem (1959) suggests that concentrations of potassium in groundwaters will usually be lower than that of sodium for two reasons, viz 1) The potassium-bearing minerals found in igneous rocks are among the most resistant to decomposition by weathering; and 2) As soon as potassium-bearing minerals break down under the influence of weathering and go into solution, several processes tend to remove potassium selectively and return it to the solid phase. Base exchange or adsorption of clays is one means by which this can be accomplished.

3.6.4 Silica

The concentration of silica in wells 9 and 13 was found to be 40 and 60 g/m^3 respectively. The nesosilicate and inosilicate minerals represent structures in which a relatively high proportion of the bonding is comprised of the linking of cations to oxygen. These bonds represent zones of weakness which can be disrupted relatively easily as compared to silicon-oxygen or aluminium-oxygen bonds. The ferromagnesian minerals, which belong largely to these two classes of silicate structures, are less stable to weathering attack than structures like the tectosilicates where silicon-oxygen bonding predominates to a greater degree. In weathering to clay minerals, however, the ferromagnesian minerals (which are common in Diamond Harbour volcanic rocks) generally give up smaller amounts of surplus silica than do the tectosilicate feldspars. Under favourable circumstances, therefore, the weathering of feldspars could constitute an important source of silica for solution in natural water (Hem, 1959).

The mechanisms of breakdown of the silicate minerals are too complex to be discussed in detail in this section. Factors such as temperature, amount of water available and freedom of water movement through the rock affect the rate at which decomposition occurs, and may also influence the type of clay mineral formed and the degree to which silica is taken into solution.

3.6.5 pH and Bicarbonate (HCO_3^-)

Total alkalinity to pH 4.5 as HCO_3^- for wells 9 and 13 was found to be 190 and 260 g/m^3 respectively (Fig. 3.17 and Table 3.1). The reactions involving dissolution of feldspars require the consumption of hydrogen ions, and a consequence of this process is the increase in pH and bicarbonate alkalinity in the water. The production of carbon dioxide in the soil zone (due to organic decay and plant respiration) is considered to be the main source of hydrogen ions for the dissolution processes. Hem (1959) suggests that waters highly charged with carbon dioxide may contain large amounts of alkalinity as bicarbonate. The complete chemical analyses of these two samples (Table 3.1) indicate that these waters are highly charged with carbon dioxide, and as a result of this the pH of these two waters is relatively low, 6.7 and 7.3.

3.6.6 Chloride (Cl^-) and Sulphate (SO_4^{2-})

The concentration of chloride in wells 9 and 13 was found to be 86 and 95 g/m^3 respectively, and for sulphate 21 and 17 g/m^3 respectively (Fig. 3.17 and Table 3.1). Igneous rocks in general do not contain large amounts of chloride or sulphate. Apatite is a commonly occurring accessory mineral in the rocks found in the Diamond Harbour area, and Hem (1959) suggests that the dissolution of this mineral is a potential source of minor concentrations of chloride. This source does not explain the high concentrations of chloride found in wells 9 and 13.

Later discussion will deal with the recharge of the Purau alluvial aquifers and the origin of these high concentrations of chloride and sulphate.

3.6.7 Water Quality Considerations

Previous sections have given detailed discussion on the possible origins of some of the chemical constituents of the alluvial groundwater found in Diamond Harbour. This section briefly discusses some of the chemical features of this groundwater in relation to the NZ Drinking Water Standards (1984).

1) Both samples tested would be suitable as sources of drinking water with some treatment for turbidity and the high concentrations of iron.

2) The low pH, particularly sample R2445/5, indicates a high concentration of dissolved carbon dioxide, but aeration brings these waters to within acceptable limits. The Langelier index of these samples is negative, and therefore these waters are likely to be corrosive to metal pipe and tap fittings.

3) The Purau Motor Camp sample has a high turbidity and this is probably due to the oxidation of iron and manganese to their insoluble forms as the water is exposed to oxygen from the atmosphere. This can be reduced by either coagulation, flocculation or filtration.

4) The nitrate levels of the two samples are well below the accepted maximum of 10 g/m^3. The J Fowler sample (well 9) has the higher concentration of 2.5 g/m^3, and this may represent local contamination of the Upper unconfined Purau Aquifer by intensive farming in the lower valley areas,

5) The concentration of iron is excessive in both cases (above 1 g/m^3), and high iron concentrations are typical of groundwater found in volcanic rocks. High iron concentrations will lead to tainting of the water, deposit formation in wells and pipes, discolouration of the water

and the staining laundry and plumbing fixtures. A number of treatments are possible, for example aeration is currently being used at the Purau Motor Camp to remove excessive iron. The groundwater from the well is sprayed over a gravel bed enclosed in a storage tank. Oxidation of the iron causes precipitation of the iron in insoluble form which adheres to the gravel bed. Gravel beds need to be regularly cleaned to remove the iron precipate.

6) Chloride concentrations are high (86 and 95 g/m^3 for wells 9 and 13 respectively) but are within acceptable limits. These concentrations are below the taste threshold of between 200 and 300 g/m^3, but the high chloride concentrations will enhance the already corrosive power of these waters.

7) Both samples have excessive manganese concentrations of 0.32 and 0.38 g/m^3. Manganese and iron are often found together in groundwaters and their presence (sometimes with ammonia) is indicative of the water being oxygen deficient. When high carbon dioxide levels are indicated, iron and manganese become soluble and minerals containing these metals are attacked. Once the iron- and manganese- enriched water is exposed to oxygen (for example, around springs or in well casings) these metals are slowly oxidised to their insoluble forms.

The high manganese levels are therefore likely to enhance problems with discolouration of water, deposit formation in wells and pipes, and the staining of laundry and plumbing fixtures. The high manganese and iron concentations and their subsequent precipitation after oxidisation probably accounts for the high turbidity of these groundwaters.

9) The absorbance measurements from the Purau Motor Camp sample indicate there is a likely presence of some organic material in the water. This is consistant with

observations of a thin oily film in both well and some surface waters.

10) Hardness values for well waters 9 and 13 are 170 and 250 g/m^3 respectively, and they are classified as moderately hard (Table 2.2). These waters will therefore to some extent cause scale formation in hot water cylinders and electric element burn out.

3.7 DEEP GROUNDWATER OF THE DIAMOND HARBOUR AREA

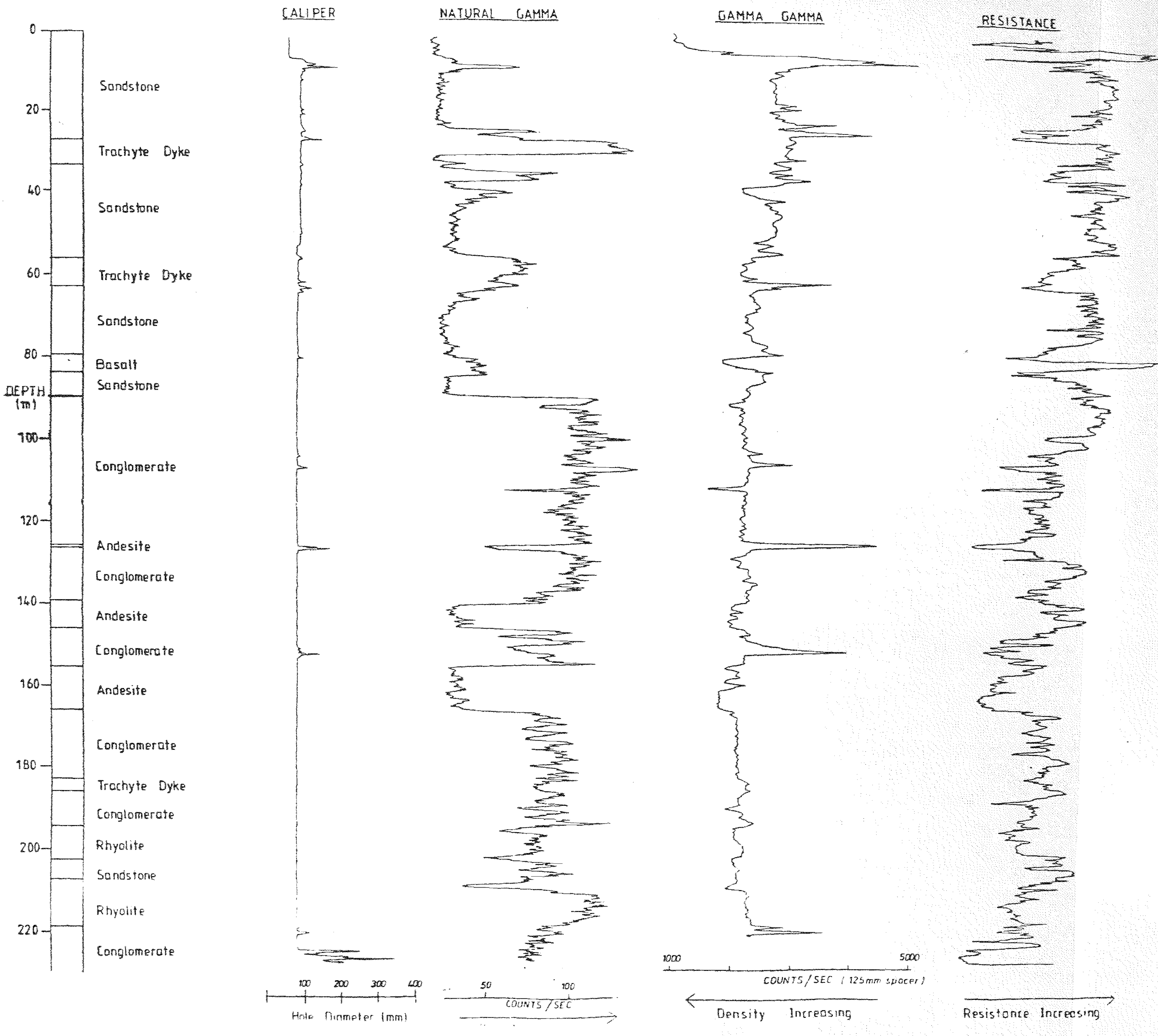
3.7.1 Introduction and Test Programme

A 220m deep well put down by the DSIR in the early 1970's and located in the Orton Bradley Valley (M36 GR 865269) struck a fractured, conglomerate zone at the base of the hole, about 210m (Fig. 3.18). The hole had to be abandoned because an artesian hard rock aquifer system had been intersected, from which flow was then calculated at approximately 10 litres/second by free flow test. Currently, flow has reduced to approximately 1 litre/second as measured by M Simpson, Senior technician DSIR, using a downhole flow meter. Simpson found that there was now no detectable flow from the base of the hole, but flow was now detected from a conglomerate zone at 103 to 106m depth (Fig. 3.18).

A large perennial spring was found in the lower Purau Valley at N36 GR 902295 and is referred to as the Sulphur Spring. This spring was monitored over a period of six months, and flows were found to vary from approximately 1 litre/second to 4 litres/second (Fig. 3.19). This spring was also found to be warm at 18°C during July 1988.

Both of these waters are interpreted to represent groundwater circulating deep within the volcanic rock. The close proximity of the Sulphur Spring to the Purau alluvial aquifers meant that this spring could be considered a likely

Fig. 3.18 Geophysical logs of the Orton Bradley Deep Well. Logging and drawing by M. Simpson, MOW, Hydrology Section.



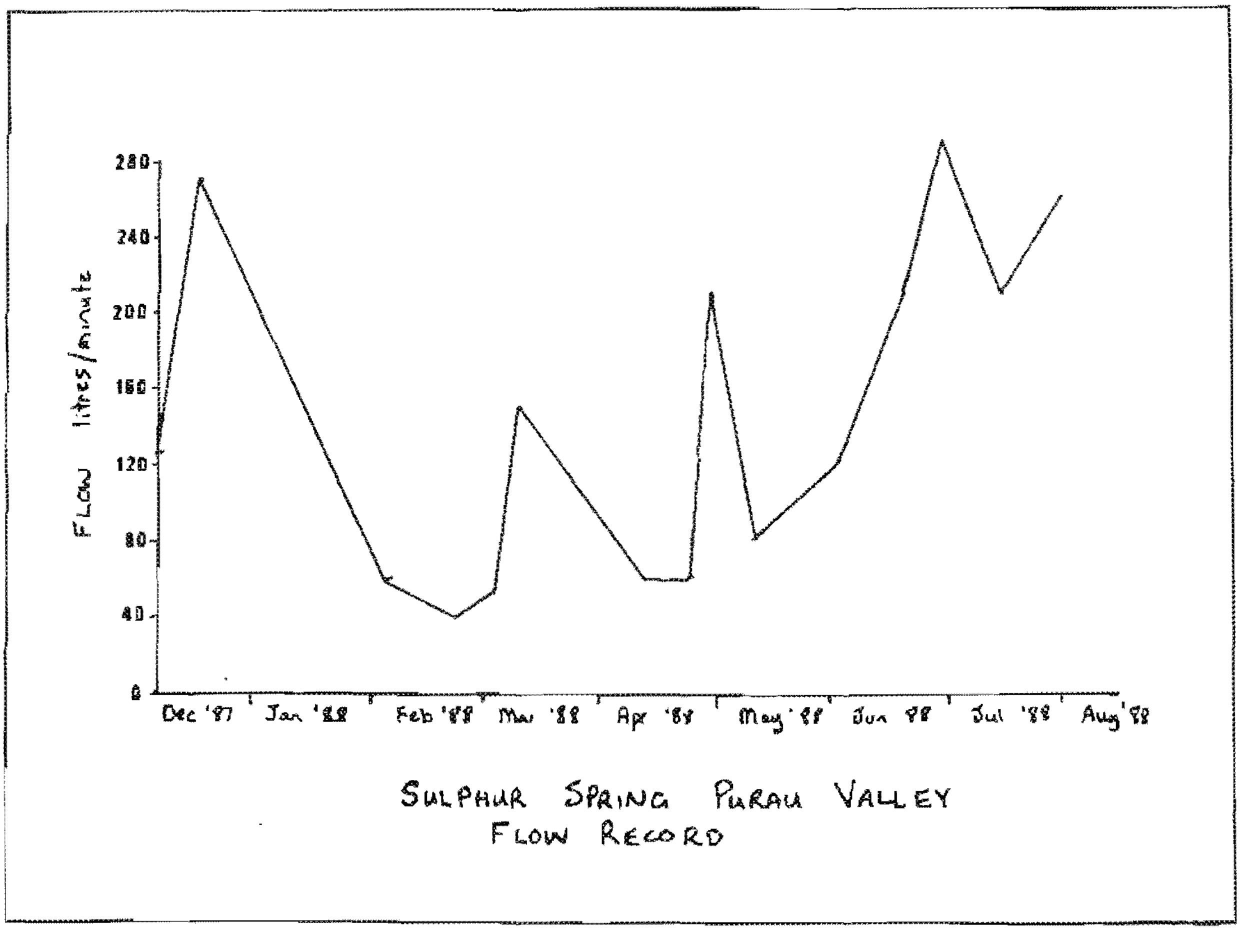


Fig. 3.19 Flow record for the Sulphur Spring, Purau Valley, December 1987 to August 1988.

source of recharge for these aquifers, and would therefore require further investigation.

To examine the relationships between this deep circulating groundwater and the shallow alluvial groundwater in Diamond Harbour chemical and isotopic analyses were taken from the Orton Bradley deep well and the Sulphur Spring.

3.7.2 Chemical Analyses of the Deep Groundwater

Chemical analyses of the Sulphur Spring and Orton Bradley deep well groundwaters are given in Fig. 17 and Table 3.2 . These two waters are characterised by high concentrations of most ionic species (compared to most Canterbury Plains groundwaters), particularly iron, sodium, calcium, magnesium and chloride. These waters have several other features in common. They are both moderately hard, turbid and have high alkalinities and dissolved carbon dioxide concentrations. A previous section discusses in some detail the possible origins of the high concentrations of ions in these deep groundwaters. The Sulphur Spring sample also has an absorbance level that indicates the likely presence of organic material in the water.

3.7.3 Isotopic Studies of the Deep Groundwater

Tritium analyses were taken for the Sulphur Spring and Orton Bradley Valley deep well groundwaters, and were found to be 0.03 and 0.18 respectively. These very low concentrations indicate no input of thermonuclear tritium (ie, post-1954 rainfall), and minimum mean ages of 50 years must be assumed for these groundwaters (M K Stewart, pers. com.).

Oxygen-18 results for the Sulphur Spring and Orton Bradley valley deep well groundwaters were found to be -7.91$^{o}/_{oo}$ and -7.97$^{o}/_{oo}$, respectively. Both these values are a little more negative but not outside the range expected for mean rainfall at higher altitudes on Banks Peninsula (M

Table 3.2 Chemical Analyses of the Sulphur Spring and Orton Bradley Deep Well Groundwaters

ANALYSIS Units g/m^3, except pH or unless otherwise stated. Sample No.:	R2445/2[ss]	R2445/4[ob]
pH	7.4	6.8##
pH after aeration	8.1	8.0
Acidity to pH 8.3 (as CO_2)	17	45
Total Alkalinity to pH 4.5 as HCO_3	260	280
Alkalinity to pH 8.3 (as CO_3)	NIL	NIL
Turbidity (NTU)	2.3*	33**
Colour (from Absorbance 270nm) TCU	2	LT1
Absorbance units (270nm, 1cm cell)	0.015	0.006
Chemical Oxygen Demand (as O)	LT4	LT4
Ammoniacal Nitrogen	LT0.04	LT0.04
Nitrite Nitrogen	LT0.005	LT0.005
Nitrate Nitrogen	LT0.05	LT0.05
Soluble Phosphate	LT0.06	LT0.06
Bromide	0.35	0.26
Sulphate	14	25
Chloride	82	130*
Floride	0.2	0.31
Calcium	51	56
Magnesium	29	25
Potassium	8.7	2.5
Sodium	47	93
Reactive Aluminium	LT0.04	LT0.04
Arsenic	LT0.01	LT0.01
Antimony	LT0.01	LT0.01
Reactive Silica (as SiO_2)	78	37
Boron	LT0.2	LT0.2
Cadmium	LT0.005	LT0.005
Chromium	LT0.02	LT0.02
Copper	LT0.02	LT0.02
Iron	1.6**	2.3**
Lead	LT0.05	LT0.05
Lithium	0.02	0.02
Manganese	0.07*	0.07*
Nickel	LT0.05	LT0.05
Selenium	LT0.005	LT0.005
Strontium	0.24	0.55
Zinc	LT0.02	LT0.02
Total Hardness (as $CaCO_3$)	250**	240**
Conductivity at 20 deg C (mS/m)	61	80
Langelier Index at 20 deg C	-0.2	-0.8

Analytical results relate only to the sample as received.
The letters LT in the above table mean "less than".
This sample does not comply with the following NZ Standard Guidlines:
outside desirable range * exceeds lower guideline limit
** exceeds upper guideline limit

ss Sulphur Spring ob Orton Bradley Deep Well

K Stewart, pers. com.). The implication is that both samples are locally derived meteoric waters precipitated at high altitude, and which under favourable geological conditions have percolated to deep levels within the volcanic rock mass.

3.8 ENVIRONMNETAL ISOTOPE STUDIES

3.8.1 Test Programme

Samples of three groundwaters were tested for the environmental isotopes oxygen-18 (^{18}O)and the radioactive isotope tritium (H^3). The aims of this part of the investigation were to confirm recharge sources and to define groundwater residence times. All isotopic analyses were carried out by the Institute of Nuclear Sciences, DSIR. Interpretations of isotopic data were provided by Dr M K Stewart.

3.8.2 Oxygen-18

No oxygen-18 information was available for the alluvial groundwater from either the Purau or Orton Bradley Valleys. The connection between these deeper groundwaters and the shallow alluvial groundwaters will be made clearer later in this chapter. At this stage the inference is made that oxygen-18 values for the alluvial groundwaters of either the Purau or Orton Bradley Valleys will be similar to the values gained for the deep groundwater discussed in section (Table 3.3).

3.8.3 Tritium

A single tritium analyses taken from the Lower Purau Aquifer (well 14) gave a tritium ratio (TR) of 0.11. This sample has a TR of virtually zero and indicates no input of thermonuclear tritium (that is post-1954 rainfall) and indicates a mean minimum residence time of 50 years and probably greater (M K Stewart, pers. com.). This TR is very close to the values gained for the deep groundwater found in

Table 3.3 Isotopic Data from the studies of: NCCB (1986), Brown (1987), Namjou (1988) and Parker (1989)

Location	Well No.	Depth (m)	Grid Reference	$\delta^{18}O$ °/oo	δD °/oo	TR	Study	Sampling Date
Orton Bradley Valley		220	N36 866 269	-7.97		0.18	Parker (1989)	1988
Sulphur Spring Purau Valley	Spring		N36 902 295	-7.91		-0.03	Parker (1988)	1988
Purau Motor Camp	13	8	M36 899 296			0.11	Parker (1989)	1988
Cass Bay	Spring		M36 850 336	-8.78			Brown (1987)	1987
Rapaki Bay	Spring		M36 845 333	-9.05	-62.7		Brown (1987)	1987
Motukarara	Spring		M36 770 200	-8.31	-55.5		Brown (1987)	1987
Kaituna Valley	M36/734	21.3	M36 47 175	-7.32		0.90	Namjou (1988)	1986
Kaituna Valley	M36/1344	30	M36 844 165	-7.21		0.03	Namjou (1988)	1986
Kaituna Valley	M36/1436	90.7	M36 823 150	-7.87		0.01	Namjou (1988)	1986
Christchurch	M36/981	178	M36 771 392	-8.9		1.1	NCCB (1986)	1976
Christchurch	M35/2266	147	M35 805 438	-9.1		0.7	NCCB (1986)	1976
Christchurch	M35/2556	143		-9.3		0.9	NCCB (1986)	1976
Christchurch	M35/2158	133	M35 819 419	-9.1		1.5	NCCB (1986)	1976

NCCB = North Canterbury Catchment Board

Purau Valley (Section 3.6) and may indicate a common source for these two waters. Further discussion on recharge sources will be given in section 3.8 (Table 3.3).

3.9 GROUNDWATER RECHARGE

3.9.1 Introduction

A number of possible recharge sources exist for the alluvial groundwater of the Purau and Orton Bradley Valleys. These include:

1) Direct infiltration of meteoric waters. This is considered to be unlikely for the Lower Purau Aquifer as this aquifer is assumed to be confined and does not outcrop at the surface in the valley. Direct infiltration may be a source of some recharge for the upper Purau aquifer and a similar aquifer assumed to be present in the Orton Bradley Valley. Both of these aquifers would appear to be unconfined and located within a metre or so of the surface, allowing rain water to percolate down through the soil column to the aquifer.

2) Hydraulic connection between the rivers and the alluvial aquifers of both valleys may provide recharge waters, however this is unlikely for the Lower Purau Aquifer.

3) Chemical and isotopic characteristics of the deep groundwater found within or near Diamond Harbour, and the alluvial groundwaters suggests that there are similarities between these two waters and that their may be some hydraulic connection between them. These deeper groundwaters were considered to be the most likely source of recharge for the alluvial aquifers found in the Purau and Orton Bradley Valleys.

To examine the possible recharge sources for the alluvial groundwaters of the Purau and Orton Bradley valleys river gaugings were taken at selected locations to determine if river water was a likely source of recharge. Water balance analysis was also performed for the Purau Valley to determine if there was any loss of local meteoric waters to groundwater. Examination of the deep circulating groundwater in relation to the recharge of alluvial aquifers is presented in this section. The origins of the deep circulating groundwater are also briefly examined in this section.

3.9.2 Surface Water Hydrology

a) Data Collection and Methodology

Surface monitoring has been carried in both the Purau and Orton Bradley catchments in order to gain an understanding of the geohydrology of these catchments, and to determine if there is any relationship between the surface and groundwater systems. Three gauging sites were used on the Purau River and two on the Orton Bradley River. On a minimum of seven occasions each river was gauged at the specified sites (Figs. 2.3 and 2.4). River flows for each site were calculated using NCCB computers and software.

An automatic river flow gauge was installed in the Purau River (M36 GR 899297) from October 1987 to July 1988. Unfortunately vandalism of the instrument has meant that flow records are only present from mid-January to July 1988. Several river gaugings were taken at different stage levels throughout the study period so that rating curves could be drawn for the Purau River. Once these stage/discharge relationships were established a hydrograph of river flow could be calculated. A brief analysis of this hydrograph is presented in this section.

b) <u>Surface Water Relationships to Groundwater</u>

Table 3.4 shows that while there is a slight difference in flows between the upper and lower reaches of the Orton Bradley River, the differences are of such a small magnitude (a few litres/second), that instrument error could account for these. No significant losses of stream flow to groundwater, or vice versa, can be detected between these two points on the Orton Bradley River.

The gaugings for the Purau River are also presented in Table 3.4. The river flow variations between the three sites on the Purau River are not conclusive enough to determine if indeed there are any losses or gains to the Purau River between these sites. Instrument error could also account for some of these variations. It is possible that some hydraulic connection exists between the Purau River and the Upper Purau Aquifer although these gaugings do not conclusively prove this hypothesis.

c) <u>Surface Flow Analysis</u>

A stream hydrograph for the Purau River (Fig. 3.20) over the period of 22/1/88 to 4/8/88 reveal that the base flow for the Purau River is almost entirely derived from the springs that flow within the Purau Valley catchment. This period has been a record dry period for the Canterbury area, and analysis indicates that flows for the Purau River amounted to less than one millimetre (flow is expressed in cubic metres/catchment area) over each weekly period.

The total catchment yield for the period of 22/1/88 to 4/8/88 has been about 59mm, of which approximately 7mm occurred as quick flow and 52mm as base flow (Table 3.5). Most of this flow occurred during the winter months when water resources are not under pressure, and clearly any management plans for the surface water resource must allow

PURAU RIVER			
DATE	SITE 1* Purau Gauge NZMS 260 M36 GR 898297 Flow m^3/s	SITE 2 Camerons Bridge NZMS 260 M36 GR 899294 Flow m^3/s	SITE 3 Blakley Ford NZMS 260 N36 GR 901291 Flow m^3/s
12/2/88	0.044	0.069	0.040
3/3/88	0.01	0.009	0.006
10/3/88	0.14	0.156	0.181
15/4/88	0.021	0.017	0.019
22/4/88	0.019	0.013	0.013
29/4/88	0.020	0.011	0.011
11/5//8	0.021	0.021	0.016
2/6/88	0.023	0.023	0.019

* These figures have been corrected for the inflow of the Sulphur Spring.

ORTON BRADLEY RIVER		
DATE	SITE 1 Lower Reach NZMS 260 M36 GR 860281 Flow m^3/s	SITE 2 Upper Reach NZMS 260 M36 GR 866270 Flow m^3/s
10/2/88	0.025	0.029
3/3/88	0.017	0.014
10/3/88	0.052	0.049
19/4/88	0.021	0.025
29/4/88	0.020	0.023
12/5/88	0.025	0.023
2/6/88	0.028	0.026

Table 3.4 River Flow Observations for the Purau and Orton Bradley Rivers, 1988

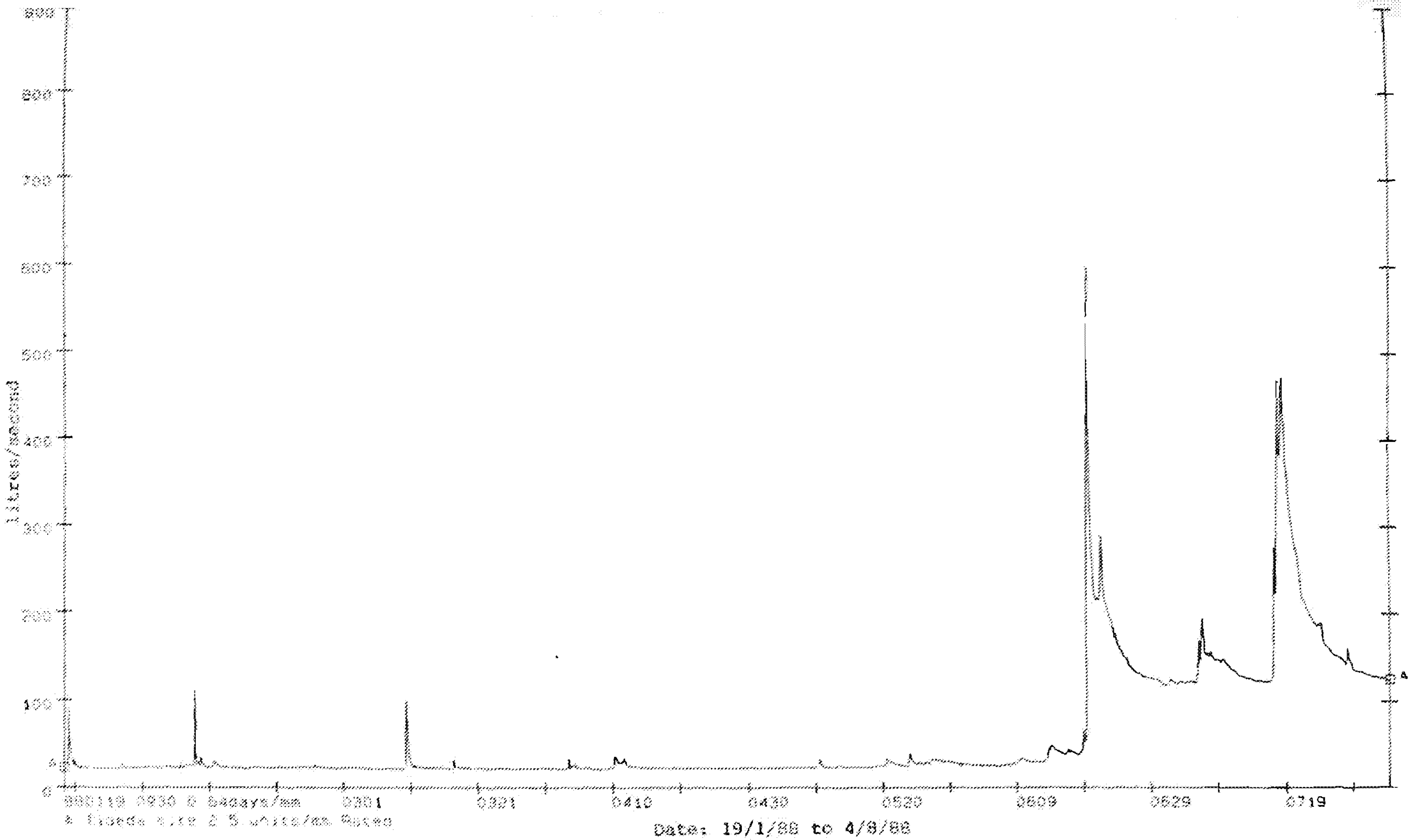


Fig. 3.20 Hydrograph for the Purau River over the period 19/1/88 to 4/8/88.

Week	Rainfall (mm)	Total flow (MM)	QF (mm)	BF (mm)	PET (mm)	AET (mm)	P-QF (mm)	$P-Q_T$ (mm)	SM (mm)	ΔSM (mm)
									-75	-17.69
22/1-28/1/88	-	0.79	-	0.79	29.0	17.69	-	-0.79	-92.69	-10.37
29/1-4/2/88	-	0.82	-	0.82	21.6	10.37	-	-0.82	-103.06	+0.08
5/2-11/2/88	19.05	0.92	0.07	0.90	18.9	18.9	18.98	18.13	-102.98	+0.2
12/2-18/2/88	14.1	0.80	-	0.80	13.9	13.9	14.1	13.3	-102.78	-2.74
19/2-25/2/88	13.1	0.82	-	0.82	18.0	15.84	13.1	12.28	-105.52	-6.22
26/2-3/3/88	-	0.80	-	0.80	16.8	6.22	-	-0.80	-111.74	+13.68
4/3-10/3/88	29.6	0.91	0.12	0.79	15.8	15.8	29.48	28.69	-98.06	+1.0
11/3-17/3/88	17.8	0.83	-	0.83	16.8	16.8	17.8	16.97	-97.06	-7.23
18/3-24/3/88	-	0.79	-	0.79	13.9	7.23	-	-0.79	-104.29	-5.02
25/3-31/3/88	-	0.77	-	0.77	11.4	5.02	-	-0.77	-189.31	-4.02
1/4-7/4/88	-	0.81	-	0.81	9.8	4.02	-	-0.81	-113.33	+18.09
8/4-14/4/88	27.8	0.89	0.01	0.88	9.7	9.7	27.79	26.91	-95.24	-5.61
15/4-21/4/88	-	0.81	-	0.81	9.2	5.61	-	-0.81	-100.85	-4.32
22/4-28/4/88	-	0.8	-	0.8	8.0	4.32	-	-0.8	-105.17	-3.57
29/4-5/5/88	-	0.81	-	0.81	7.0	3.57	-	-0.81	-108.74	+16.69
6/5-12/5/88	23.7	0.84	0.01	0.83	7.0	7.0	23.69	22.86	-92.05	+10.2
13/5-19/5/88	17.2	0.85	-	0.85	7.0	7.0	17.2	16.35	-82.05	+7.37
20/5-26/5/88	14.4	0.98	0.03	0.95	7.0	7.0	14.37	13.42	-74.68	-6.37
27/5-2/6/88	-	1.04	-	1.04	7.0	6.37	-	-1.04	-81.05	+6.1
3/6-9/6/88	11.1	0.96	-	0.96	5.0	5.0	11.1	10.14	-74.95	+10.92
10/6-16/6/88	16.0	1.13	0.18	1.05	5.0	5.0	15.92	14.87	-64.03	+43.08
17/6-23/6/88	50.0	6.33	1.92	4.41	5.0	5.0	48.08	43.67	-20.95	-5.0
24/6-30/6/88	-	4.89	-	4.89	5.0	5.0	-	-4.89	-25.95	+5.18
1/7-8/7/88	9.8	5.59	0.33	5.26	4.29	4.29	9.47	4.21	-20.77	-5.71
9/7-14/7/88	-	4.15	-	4.15	5.71	5.71	-	-4.15	-26.48	+45.92
15/7-24/7/88	57.9	12.09	4.84	7.25	7.14	7.14	53.06	45.81	+19.44	-2.86
25/7-28/7/88	-	3.14	-	3.14	2.86	2.86	-	-3.14	+16.58	-5.0
29/7-4/8/88	-	4.75	-	4.75	5.0	5.0	-	-4.75	+11.58	

Table 3.5 Water balance calculations for the Purau Valley over the period 21/1/88 to 4/8/88, where QF = Quickflow, BF = Baseflow, AET = Actual Evapotranspiration, PET = Potential Evapotranspiration, Q_T = Total flow, SM = Soil moisture level and ΔSM = Change in soil moisture level.

for the extremely low flows that occur during the summer months.

3.9.3 Water Balance Analysis

a) Data Collection and Analysis

A simple water balance equation was used to estimate the amount of precipitation lost over the balance period to recharge groundwater. Vandalism to stream flow instruments has meant that calculations are limited to the period of 22/1/88 to 4/8/88. A complete summary of water balance calculations is given in Appendix Nine.

The water balance of a small drainage basin can be expressed by the following equation :

$$R = P - (AET + Q_f) - Q_b - \quad SM$$

where R = total recharge to groundwater

P = total precipitation over the catchment area

AET = actual evapotranspiration

Q_f = quickflow

Q_b = baseflow

ΔSM = change in soil moisture

1) Precipitation

Precipitation was measured over a period of one year from June 1987 to July 1988 using two high capacity automatic Belfort rain gauges. To determine altitudinal differences in precipitation one gauge was located near Mt Herbert (M36 GR 887243) and the second was located in Diamond Harbour (M36 GR 887303).

Using the isohyetal technique a total of 321mm of precipitation was recorded for the study period.

2) Evapotranspiration and Soil Moisture Deficit

Christchruch airport potential evapotranspiration (PET) figures have been used in these water balance calculations for the period of 22/1/88 to 28/4/88. For the remaining period average weekly figures of PET from Ashley Forest were used because the Meterological Service does not calculate PET figures over the period May to September of each year. The Ashley Forest figures have been averaged over a period of several years by Forestry Research Institute (FRI) staff, and are considered to be typical of areas like Diamond Harbour (R Jackson, pers. com.).

Over a normal year there will be a period when precipitation exceeds PET (usually winter) and AET will occur at the potential rate. As the soil dries AET falls below the potential rate (summer through autumn) and the effect of this must be shown in any water balance calculations. The procedure used in this study to calculate AET is outlined in Appendix Nine.

3) Stream Flow

Standard NCCB techniques were employed to separate quickflow and baseflow from the Purau River hydrograph, for each storm event that occurred over the balance period. Details of this procedure are outlined in Appendix Nine.

b) Water Balance Data Interpretation

Table 3.5 shows a summary of the water balance calculations for the Purau Valley. Up until the week beginning 15/7/88 there existed a soil moisture deficit within the soil profile. If the 1988 year had been a year of average rainfall, a soil moisture surplus should have registered by this time. For the first six months of 1988 the soil moisture deficit was so severe that any rainfall events produced virtually no quickflow.

From the 15/7/88 a soil moisture surplus existed within the soil profile until the end of the balance period. Calculations reveal that of the total of 321mm of precipitation only 11.6mm or 3.6% was avaliable for groundwater recharge.

Due to the exceptionally dry year it appears that very little precipitation has been lost to groundwater recharge. Namjou (1988) calculated that 4.5% of total precipitation had been lost to recharge groundwater in the Kaituna Valley. On the basis of this study and the study of Namjou (1988), it appears that annual recharge to volcanic rock aquifers in the Diamond Harbour and Kaituna Valley areas is limited to less than 5% of annual precipitation. This figure will vary slightly depending on whether the year has been wetter or drier than average.

c) Data Limitations

Several assumptions have been made in calculating a water balance for the Purau catchment. The most likely source of error will involve calculations of rainfall distribution over the catchment (R Jackson, pers. com.). Depending on the number and distribution of rain gauges across the catchment, rainfall totals will at best be accurate to within 10% of the true figure (R Jackson, pers. com.). An error of 10% for precipitation means that precipitation totals for Purau Valley will be accurate to within +/- 32mm. Clearly the calculated recharge component of 11.6mm could be accounted for by errors in the calculation of rainfall for the Purau Catchment.

Other assumptions (for example, the assummed soil moisture deficit at the beginning of the balance period, and the assumptions made in calculating AET) will probably have a greater inherent accuracy compared to calculations of total precipitation (R Jackson, pers. com.).

3.9.4 Relationship Between Deep and Alluvial Groundwater

a) Purau Valley

Several common features exist between the Sulphur Spring groundwater and the alluvial groundwaters of the Purau Valley, and they indicate that these alluvial groundwaters are principally recharged from the same source that supplies the Sulphur Spring. These features include:

1) The proximity of the Sulphur Spring to the Purau alluvial aquifers.

2) Hydrological, isotopic and geologic evidence suggests that the alluvial aquifers of the Purau Valley are not in the main, recharged from the Purau River, and therefore other sources of recharge must exist.

3) Chemical profiles suggest that the Sulphur Spring groundwater and the alluvial groundwaters of the Purau Valley are similar. The Sulphur Spring and well 13 samples both indicate the presence of organic material in the water.

4) Tritium analyses indicates that the Sulphur Spring groundwater and the alluvial groundwaters of the Purau Valley have similar, very long residence times (50 years or greater). The interpreted volume of both Purau aquifers is very small (about 145,000m^3 if the approximate dimensions of the Lower Purau Aquifer are 600m x 64m x 3.78m) and the alluvial aquifers could not store groundwater for this length of time, hence the high flow of the Sulphur Spring must be derived from storage within the volcanic rock.

5) Oxygen-18 analyses indicates that the Sulphur Spring groundwater and the alluvial groundwaters of the Purau Valley originally were locally derived (Banks Peninsula) meteoric waters.

6) The slightly elevated temperatures of the Sulphur Spring groundwater and the alluvial groundwaters of the Purau Valley, 18°C and 14.5°C respectively, compared with 10 to 12°C for Canterbury Plains groundwaters, also indicates a similar origin.

b) Implications for the Orton Bradley Valley

No groundwater samples were taken from the gravels that were interpreted to represent a small unconfined aquifer in this valley. However, based on the evidence from the Purau Valley and the known presence of deep groundwater in the Orton Bradley Valley, it seems reasonable that recharge of this alluvial aquifer is from deep circulating groundwaters with residence times of 50 years or more.

3.9.5 The Origin of the Diamond Harbour and Lyttelton Harbour Mildly Thermal Waters

The previous section discussed the relationship between the deep circulating groundwaters of Diamond Harbour and the shallow alluvial groundwaters found in the area. The evidence suggests that the deep circulating groundwater provides most, if not all, recharge to the alluvial aquifers.

This section briefly examines the origin of the mildly thermal groundwater of Diamond Harbour and to do this the writer includes data from other Lyttelton Harbour mildly thermal springs waters

Table 3.6 presents chemical analyses from five thermal springs found in Lyttelton Harbour (see also Table 3.3).

	Cass Bay	Rapaki Bay	Motukarara	Lyttelton Rail Tunnel	Ferrymead
ANALYSIS					
Units g/m^3, otherwise stated.					
Temperature ^{o}C	28	28	28	-	-
pH	8.2	7.9	8.4	7.1	8.1
Lithium	LT0.05	LT0.05	LT0.05	-	-
Sodium	425	440	100	162	152
Potassium	183	165	2.8	18	5.4
Calcium	11	10	18	144	-
Magnesium	13	8.5	12	110	-
Rubidium	LT0.05	LT0.05	LT0.05	-	-
Caesium	LT0.05	LT0.05	LT0.05	-	-
Chloride	263	237	117	520	215
Sulphate	40	10	20	110	31.5
Boron	2.1	2.3	LT1.0	LT0.2	-
Silica	96	100	35	-	20
Total bicarbonate	863	961	174	349	137

The letters LT in the above table means "less than".

Table 3.6 Lyttelton Harbour Mildly Thermal Springs

a) Cass Bay
b) Rapaki Bay
c) Lyttelton road tunnel
d) Motukarara
and e) Ferrymead.

Temperatures from these thermal waters range from about $17^{o}C$ to $27^{o}C$, compared to $18^{o}C$ for the Sulphur Spring and $14.5^{o}C$ for the Purau Motor Camp well. Chemical comparisions of the listed thermal waters also reveals that they are highly alkaline, with high concentrations of sodium, potassium and chloride.They are similar in chemical composition to the Sulphur Spring, Purau Motor Camp well and Orton Bradley deep well waters.

While generally the correlation between chemical and isotopic composition is not simple and straight forward, there are instances where comparision of chemical and isotopic data has been useful (Gat, et. al., 1981). In cases where underground temperature is not high enough to enable significant isotopic exchange between water and rock, and where the total salinity of the waters is high, coupled chemical and isotopic analyses can be adopted usefully to distinguish source regions and path lines of thermal fluids emerging in the same area (Gat, et. al., 1981). Figure 3.21 suggests a relationship between oxygen-18 ratios and chloride values for three thermal groundwaters in or near Lyttelton Harbour, and for the deep groundwater sources from this study. This suggests a source line for these waters that can be directly related to locally derived meteoric waters. Oxygen-18 and deuterium values for the Motukarara and Rapaki thermal springs are also plotted against the local meteoric water line (Fig. 3.22). Both springs plot very close to the meteoric water line, indicating that these waters are deep circulating (hence, the higher than usual water temperatures) and of meteoric origin.

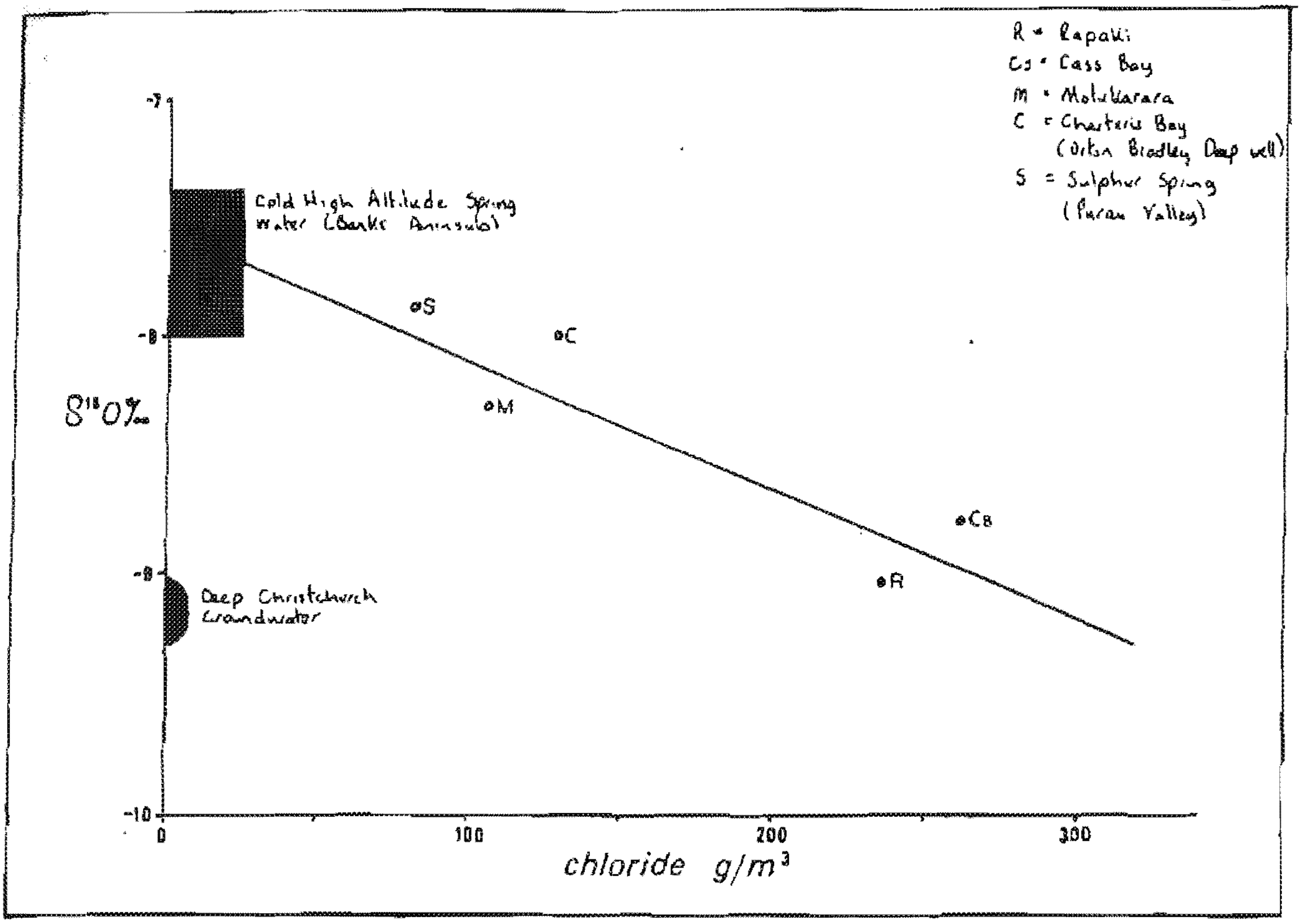


Fig. 3.21 Coupled chemical and isotopic data of High Altitude Spring waters and Lyttelton Harbour mildly thermal waters.

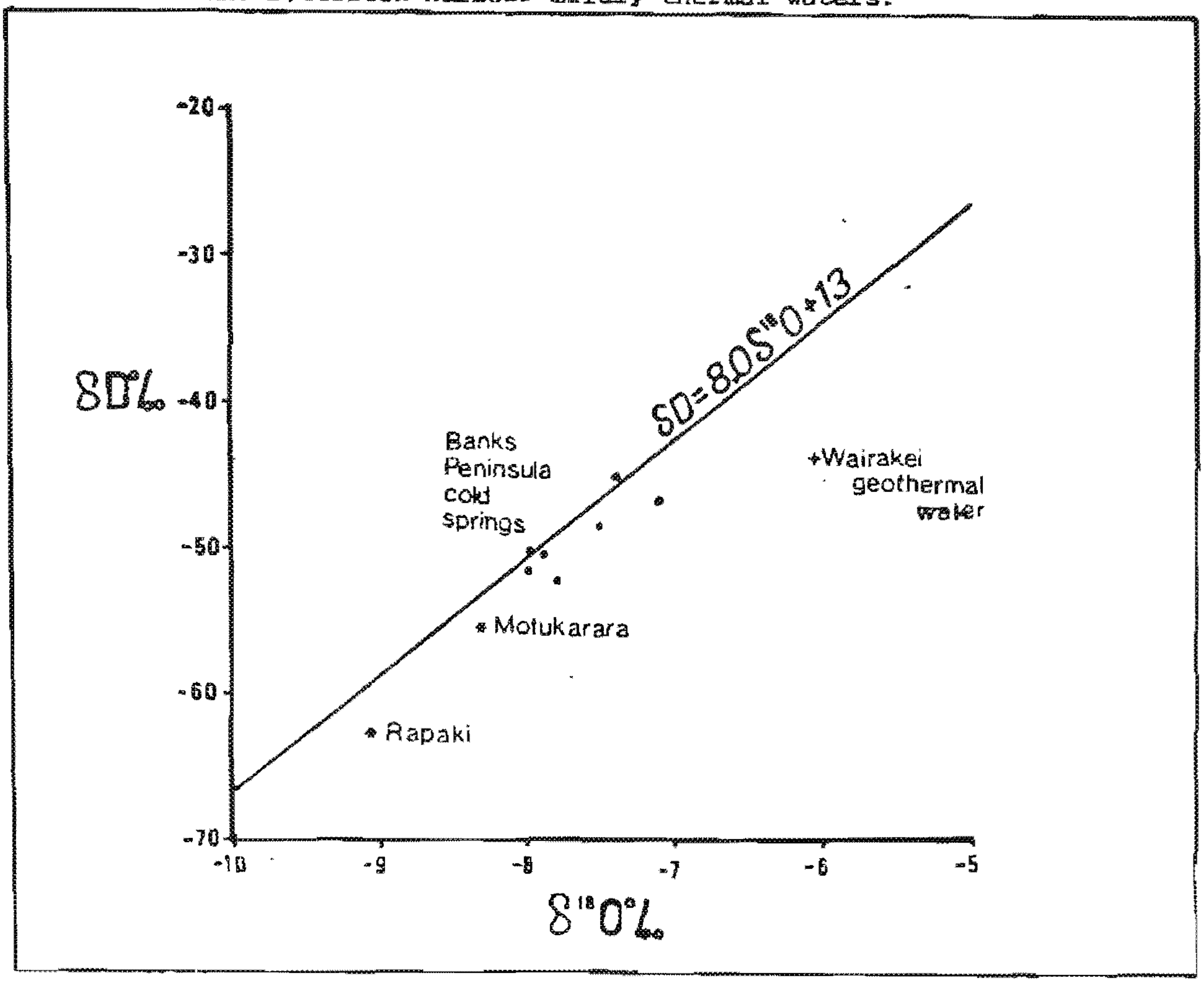


Fig. 3.22 Plot of deuterium and oxygen-18 data for two mildly thermal

The conclusion from these simple observations is that the thermal waters of Lyttelton Harbour (including those from this study) are locally derived meteoric waters of great age (50 years or greater for the Sulphur Spring sample) that have circulated to great depth, and have returned to the surface where geological conditions are favourable. The considerable flow of some of these springs (for example, the Sulphur Spring and Orton Bradley deep wells) indicates a considerable volume of storage in the volcanic rock. Assuming a residence time of 50 years, and an average flow of one litre/second for the Sulphur Spring and Orton Bradley deep well waters, then both of these sources must have a reservior of approximately $1.5 \times 10^6 m^3$!

The high concentrations of most ionic species found in these warm waters can be accounted for by dissolution processes involving the minerals found in the volcanic rock, the length of travel through the rock of individual water molecules, and the time taken for this process.

3.10 A HYDROGEOLOGIC MODEL FOR THE VALLEY FLOOR AQUIFER SYSTEMS

3.10.1 Purau Valley

Two aquifer systems exist in the Purau Valley:
1) Two alluvial aquifers are found within the Purau Valley alluvial and marine sediments. These consist of a Lower confined main aquifer interpreted to represent one or more infilled river channels (hydraulic evidence suggests one channel is about 64m in width), and an Upper more laterally extensive (up to 400m in width but only about 300m in length) river deposit representing an unconfined aquifer. Chemical, isotopic and flow information suggests that these alluvial aquifers are recharged from the second aquifer system. 2) The second aquifer system provides storage for groundwater within the volcanic rock. This system comprises extensive fracture systems that by implication exists throughout the Lyttelton Harbour area, including the study

area. This water is old (mean residence time of 50 years) and is highly mineralised in comparison with most Canterbury Plains groundwaters (Fig. 3.23).

Geological, hydraulic and isotopic evidence suggests that the alluvial aquifers are very small in volume (for example, the Lower Purau Aquifer is estimated to be about $145,000m^3$) and, hence their storage capacity is limited, while the deeper hard rock aquifer systems must be several millions of cubic metres in volume.

Recharge for the lower Purau aquifer is by direct flow from the volcanic aquifer system into the gravel aquifer. Recharge to the upper Purau aquifer is probably due to leakage from the lower Purau aquifer, together with possible dilution from meteoric and Purau River water.

3.10.2 Orton Bradley Aquifer Systems

Two aquifer are also found within the Orton Bradley Valley. Resistivity information suggests that a one to three metre thick alluvial gravel aquifer has been deposited in the lower Orton Bradley Valley. There are no wells or drill hole information to confirm these interpretations.

A deep drill hole located in the Orton Bradley Valley has intersected an artesian hard rock aquifer system which contains highly mineralised water having high concentrations of most common cations and anions (in comparison with most Canterbury Plains groundwaters) with a mean residence time of 50 years or more. On the basis of evidence found in the Purau Valley, leakage of groundwater from the volcanic rock via fracture systems probably accounts for recharge to the alluvial gravels of this valley. The limited extent of these gravels indicates that they will only supply a limited quantity of groundwater to supply a few households.

3.11 SYNTHESIS

Geophysical investigations, drill hole and hydraulic data reveal that two sandy gravel aquifers are to be found within the shallow (<15m deep) alluvial sediments infilling the lower Purau Valley. These aquifers comprise a confined lower aquifer interpreted to represent a narrow (approximately 64m width) infilled river channel, and an upper unconfined laterally extensive aquifer of alluvial sands and gravels. Geophysical evidence suggests that a small shallow unconfined gravel aquifer also exists within the sediments infilling the Orton Bradley Valley.

Chemical analyses of these alluvial groundwaters reveals that they have high concentrations of sodium, potassium, calcium, magnesium, chloride and bicarbonate alkalinity. Isotopic information also reveals that these alluvial groundwaters are locally derived meteoric waters with a mean residence time of 50 years or greater.

Chemical and isotopic analyses of the Sulphur Spring and Orton Bradley deep well waters indicates that they also have high concentrations of the above ionic species and have similar residence times to the alluvial groundwaters. These deep groundwaters appear to have been derived from local precipitation which has percolated through and has been stored within volcanic rock reservoirs. Recharge to the alluvial aquifers of the Purau Valley has been found to occur from the hard rock volcanic aquifers which supply the Sulphur Spring. By implication similar recharge to the Orton Bradley alluvial aquifer probably occurs from the hard rock aquifers that supply the Orton Bradley deep well.

CHAPTER FOUR

HIGH ALTITUDE SPRINGS

4.1 INTRODUCTION

4.1.1 Objectives and Methodology

Chapter Two included a summary of the findings of previous studies on high altitude springs found on Banks Peninsula. Chapter Four discusses the High Altitude Springs of Diamond Harbour, and the aims of this part of the investigation were 1) to identify the geological formations that provided the largest resource of spring water; and 2) if possible develop a model that adequately explained the behaviour of the springs found in the study area. Such a model would assist in developing management strategies for the groundwater resources of the Diamond Harbour area.

The term 'High Altitude' is used to differentiate between springs that are found in the lower valley areas which are interpreted to derive their flow from deep circulating groundwater, and those springs that are seen to exit from individual lava flows commonly at high altitude and near ridge tops. These latter 'high altitute' springs are usually of low (2.5 litres/minute) to high (up to 60 litres/minute) flow and isotope data suggests groundwater residence times of a few years up to 10 to 25 years. Lower valley spring waters are interpreted to have residence times of several tens of years to greater than 50 years, and often have flows of 60 litres/minute or more

A flow gauging station was set up on a perennial bedrock High Altitude spring located in the upper Purau Valley from 26/7/88 to 16/9/88. Constant flow records were gained for a period of about one month, and spring waters were sampled daily for a period of 35 days for oxygen-18 analyses. Any rainfall events that occurred over the period were also sampled for oxygen-18 analyses, whilst two tritium analyses were taken from this spring in March and October of 1988.

On the basis of field observations gained in Akaroa County, Sanders (1986) developed a model that attempted to explain the behaviour of the High Altitude Springs found in his area. Sander's model is discussed in this chapter as a basis from which a revised model is presented.

4.1.2 Spring Distribution in the Diamond Harbour area

Figure 4.1 presents information regarding the distribution of springs in Diamond Harbour (see also Fig. 2.5), which have been grouped according to the following geological formations: 1) Herbert Peak Hawaiite; 2) Orton Bradley Formation; and 3) other geological formations. Of the approximately 300 springs of all discharge magnitudes, the majority of the high magnitude (> 15 litres/minute) are to be found in the Herbert Peak Hawaiite and Orton Bradley formation lavas. Geological factors are believed to be responsible for this distribution and are discussed in later sections.

Springs are often found near ridge tops in the study area (Plate 4.1), and this observation has also been made in past studies, for example by Sanders (1986). In the past it has been difficult to explain the presence of high flowing perennial springs so close to ridge lines,however on close inspection, calculations usually reveal that there is a significant volume of potential reservior rock lying above each spring.

Only a small proportion of springs can be seen actually exiting from volcanic bedrock reservoirs, as most springs exit through either mixed or volcanic colluvium. For perennial springs that exit through colluvium it is assumed they derive their flow primarily from bedrock reservoirs (Fig. 4.2).

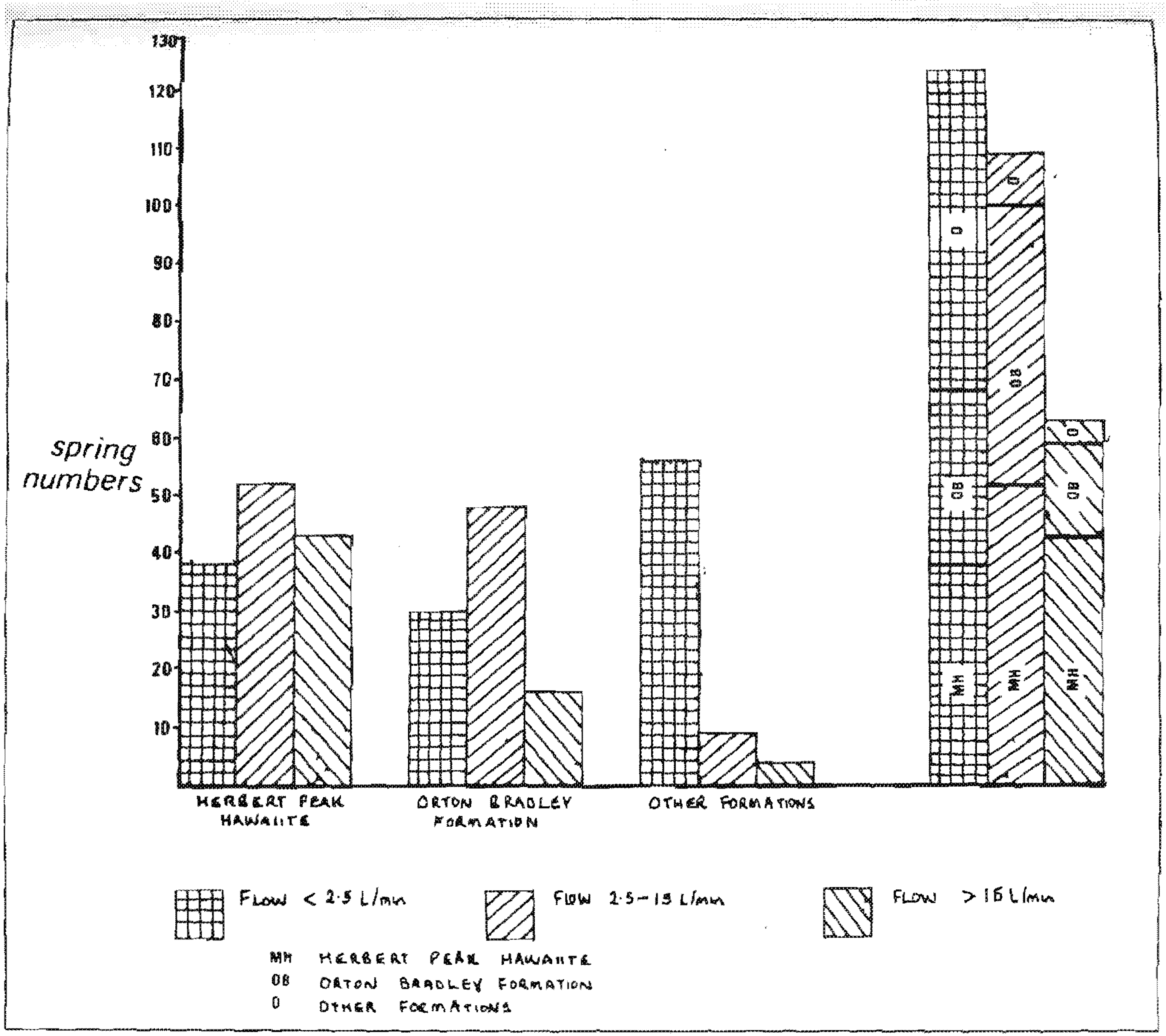
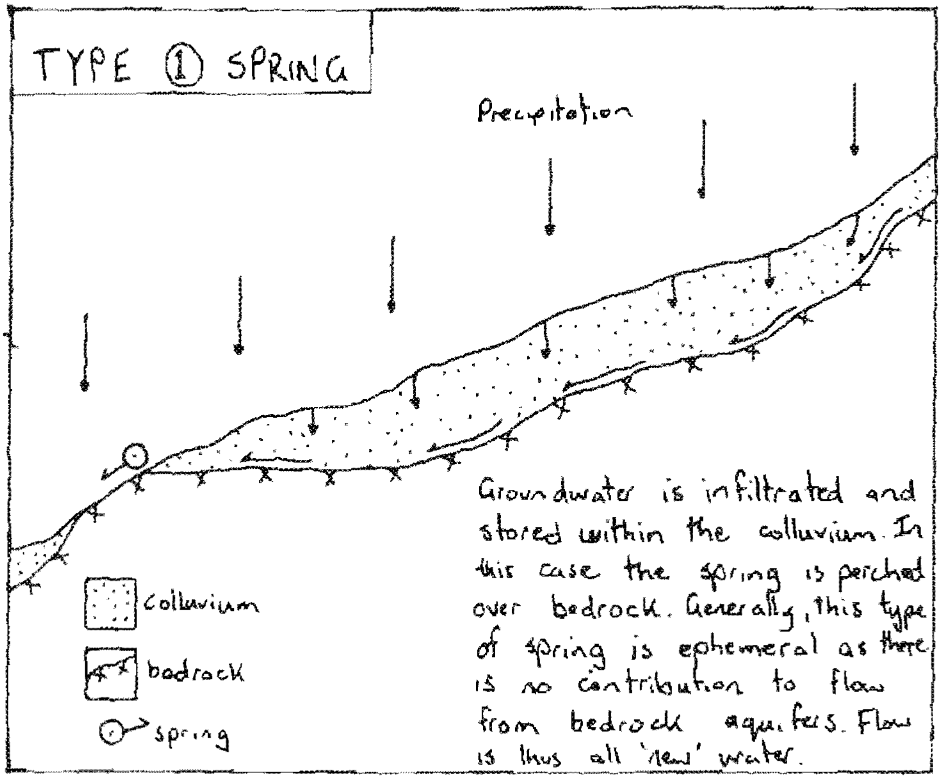


Fig. 4.1 Spring distribution in the Diamond Harbour area.



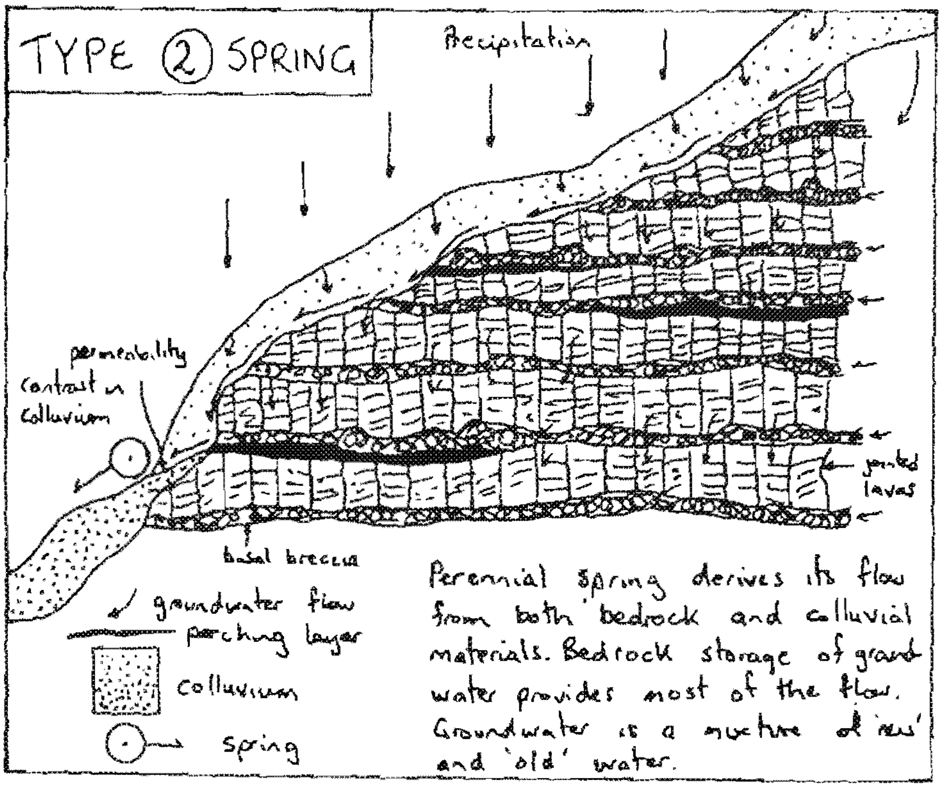


Fig. 4.2 Spring models showing components of flow for two types of High Altitude Spring found in Diamond Harbour. Type 1 springs derive their flow entirely from soil moisture storage, Type 2 springs derive their flow from soil moisture and bedrock storage.

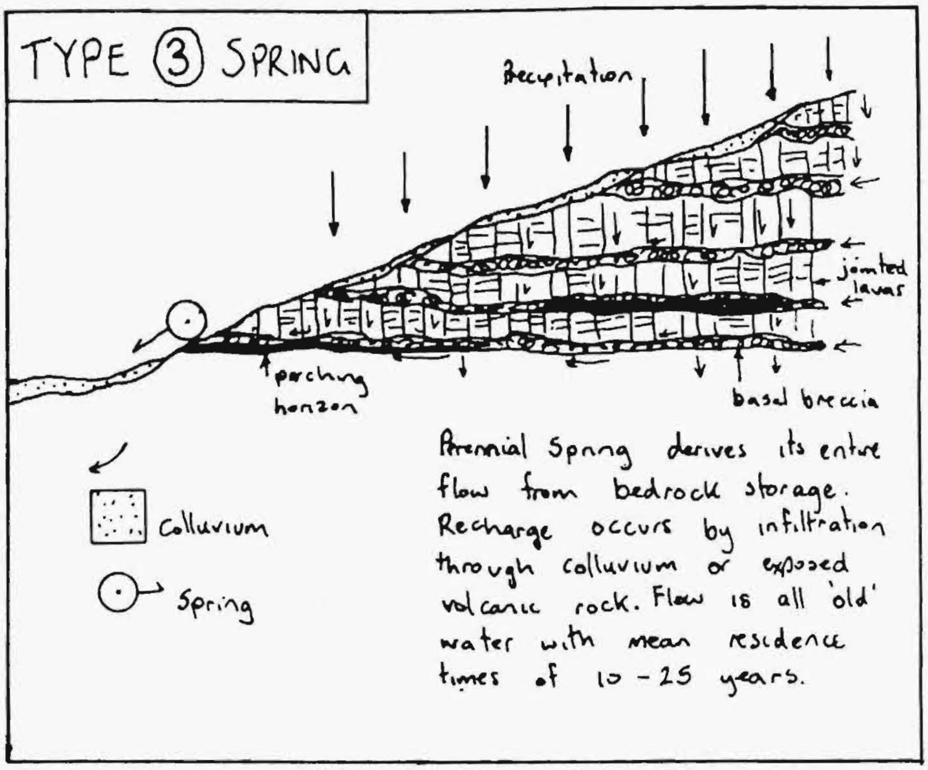


Fig. 4.2 (contd.) Type 3 springs derive their flow entirely from bedrock storage.

Plate 4.1 Upper Purau Valley. Note the dark green patches above the prominant lava bench, each of which is a perennial bedrock spring. This area includes springs X1 to X18.

4.2 THE GEOLOGICAL OCCURRENCE OF SPRINGS

4.2.1 Lava Flow Character

a) Orton Bradley Formation Lavas

Sewell (1985) notes that the lowest (oldest) aa lavas of this formation dip gently ($<10^{o}$) to the south east, while the upper (youngest) aa lavas dip gently (10^{o} to 20^{o}) to the north west. Separating the two thicknesses of lava flows are the volcaniclastic lake sediments and thick tuff deposits that comprise up to 20 percent of the Orton Bradley Formation.

Jointing in the Orton Bradley lavas can be in the form of well-developed columns or in places very irregular (ie variable spacing, and the joint could be straight or wavy in character). Springs are found to be associated with either joint pattern. Flows vary in thickness from 1 to 30m, and 2-3m thick flows are commonly separated by flow breccias less than one metre thick. Joint persistence can vary but usually extends the full flow thickness. Joint aperture also can vary from zero up to an observed maximum of 0.1m. Orton Bradley lava materials on the whole are fresh to only slightly weathered.

A number of springs are associated with the lower sequence of lavas where they outcrop as the feature known as Tableland Spur (M36 GR 860260, Figs. 2.2 and 2.5). Direct infiltration of meteoric water on this near flat surface occurs to supply storage for the dozen or so ephemeral springs that are to be found on Tableland Spur. These springs have maximum discharges of up to 40 litres/minute.

Those springs associated with the upper lavas of the Orton Bradley Formation are often perennial and of high magnitude, reflecting the larger volume of reservoir rock available. The regional dip of these lavas is to the northwest and influences the direction of groundwater movement. Many high magnitude springs are to be found on the western side of the Diamond Harbour Dip-slope (eg. M36 GR 880263) in the upper Orton Bradley Valley. As the upper lavas dip northwest into the Orton Bradley Valley it would be expected that groundwater would exit as springs where geological conditions are favourable. This is not always the case, as high flowing springs on the eastern side of Mt Bradley exist and appear to flow against the regional dip of these lavas. The presence of local confining layers and the regular to irregular joint pattern found in these lavas may explain this apparent anomaly.

b) Herbert Peak Hawaiite Lavas

North of Mt Herbert the Herbert Peak Hawaiite lava flows dip gently to the north away from an assumed vent in the vicinity of Mt Herbert. These lavas act as a virtual flat-lying cap to the area of highest elevation and rainfall in the study area. A notable feature of these lavas is the very well developed columnar jointing (Plate 4.2) that can be seen in outcrop. Irregular jointing can also be seen in many flows. Flows are often between 20 and 40m thick, although some are less than 6m thick, and most are separated by autobrecciated layers.

Vertical jointing is seen to persist through the entire massive portion of most flows, and spacing can vary from a few tens of centimetres up to about 1.6m. Aperture can vary significantly within the same joint from a few millimetres up to 0.40m, however most are between 0.01 and 0.1m.

A feature of the Herbert Peak Hawaiites that may assist in the lateral movement of groundwater is the tendency for a horizontal joint set to be well developed (Plate 4.3). Horizontal joint sets tend to be more closely spaced (0.02 to 0.1m) compared to the dominant vertical set, with apertures for usually in the order of a few millimeters. These horizontal joints are probably the result of layers

Plate 4.2 A prominant outcrop of columnar jointed Herbert Peak Hawaiites found in the upper Purau Valley. (N36 GR 901248)

Plate 4.3 An outcrop of jointed Herbert Peak Hawaiite showing both vertical and horizontal joint sets which divide the rock mass into 'plates'. (M36 GR 899244)

within a lava flow cooling at different rates and not an exfoliation feature as Yetton (1983) suggests. The effect of this horizontal joint set, with combined with the dominant vertical set, is to divide each column into a series of 'plates' a few centimetres in thickness and bounded by vertical joints.

Lava materials are usually fresh to slightly weathered, although where springs are seen to exit from fractured lavas the grey/black hawaiite has often been leached by circulating groundwaters to leave a whitish alteration product.

It is clearly a combination of geologic and geomorphic features that contribute to making the Herbert Peak Hawaiite lavas the most significant reservior rocks in the Diamond Harbour area. Acting as a flat lying capping in the pathway of rainbearing winds, high rainfall is easily and quickly infiltrated and stored in layers of closely jointed lava flows. A combination of closely jointed lavas and associated thin, laterally discontinuous tuff deposits and lahars accounts for the large number of springs that exit from this formation (Plate 4.1).

The lack of significant pyroclastic deposits (eg major tuff cones) within the Mt Herbert Hawaiite means that groundwater can easily percolate to lower altitudes, before exiting as springs perched over thick relatively impermeable rock masses, such as the lake sediments and tuff deposits in the Orton Bradley Valley (Fig. 4.3). Some groundwater must also travel even further via preferential fracture systems to great depth (ie below sea level), occasionally to resurface as mildly thermal waters (eg The Sulphur Spring, Purau Valley).

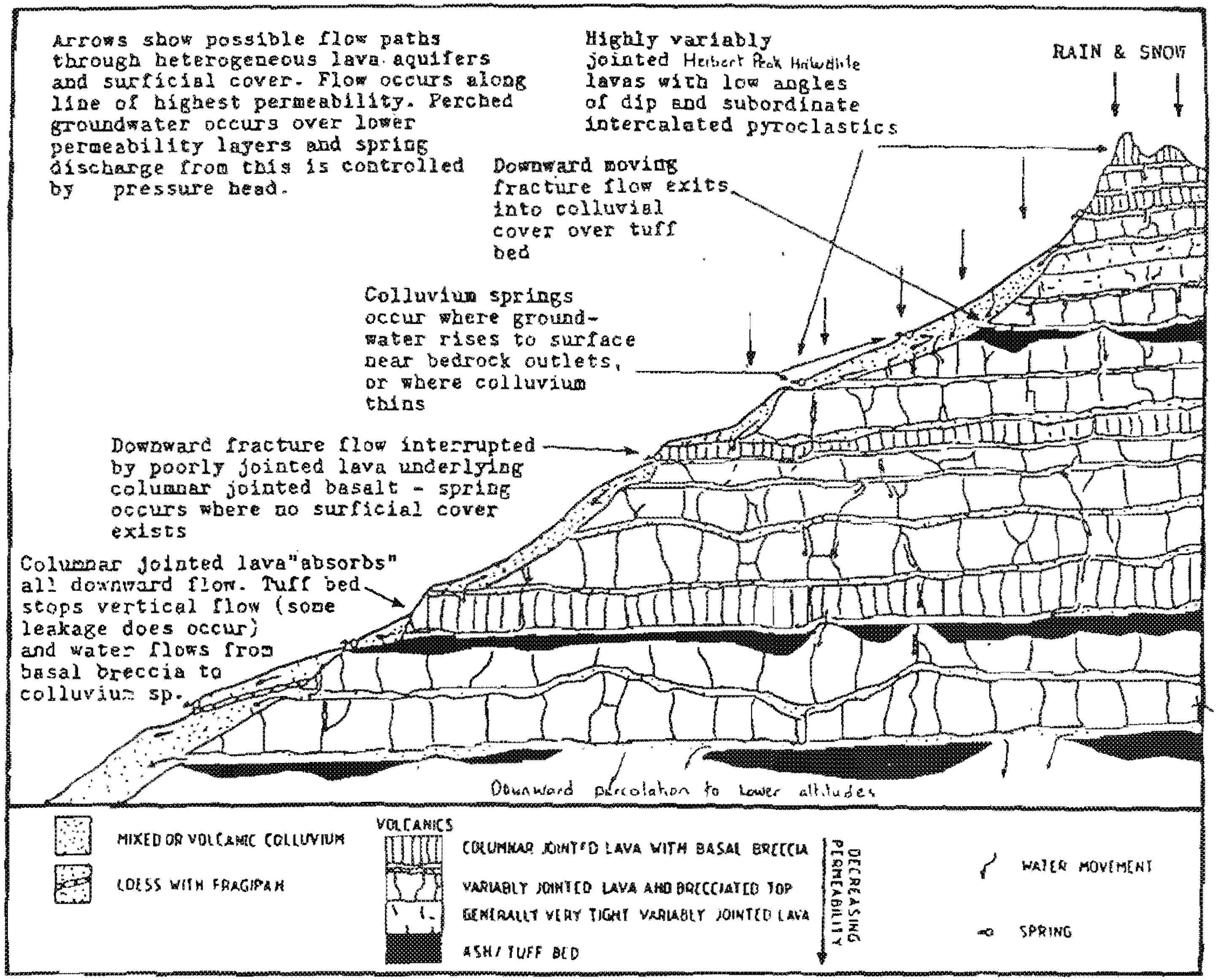


Fig. 4.3 Schematic diagram showing possible flowpaths in the geological materials of the Diamond Harbour area. (After Sanders, 1986)

c) Other Volcanic Formations

A number of springs are also associated with the Stoddart Basalt lavas. With a few exceptions, these are usually ephemeral, low flow magnitude springs which exit from columnar to irregularly jointed lavas (Plate 4.4) averaging 2 to 3m in thickness. Stoddart Basalt lavas can be up to 45m in thickness, for example on the flanks of the Diamond Harbour dip-slope (M36 GR 888279).

Several large springs also exit from the base of the cliffs that flank the dip-slope in the Purau Valley (M36 GR 890281). These are high magnitude perennial springs that exit from Stoddart lavas perched over older, more weathered Lyttelton lavas. It may be that groundwater is channelled over an older Lyttelton erosion surface to exit as springs in this area. In general, however, only a small number of the total springs mapped are associated with the Stoddart lavas (Fig. 2.5).

4.2.2 Groundwater Movement in Surficial Materials

Almost all of the High Altitude Springs in the study area are located where thicknesses of up to 1.8m of either mixed or volcanic colluvium form a mantle over the volcanic bedrock (Fig. 2.5). The hydraulic conductivity of colluvial materials is seen to vary from place to place depending on the ratio of coarse to fine materials. A volcanic colluvium composed of dominantly gravel-sized clasts of volcanic debris will have a high hydraulic conductivity (around 10^{-3} to 10^{-4} m/s) compared to a mixed colluvium composed of dominantly clay/silt sized particles. Sanders (1986) quotes a range of hydraulic conductivities for colluvium from 1.6×10^{-7}m/s to 1.1×10^{-5}m/s which were probably derived from fine grained colluvial materials.

Colluvial materials have an important role to play in relation to the recharge processes of high Altitude springs.

With the exception of a few low magnitude ephemeral springs that probably maintain their flow entirely from soil moisture storage during the wet season, the surficial cover stores water after a rain event before transferring it to the bedrock/colluvium boundary, where recharge of volcanic reservoirs can take place. Some precipitation losses will occur by surface runoff and soil through flow, however, the 'water holding' capacity of the surficial cover allows rainfall to be temporarily held within the soil before slow percolation to underlying bedrock aquifers (Fig. 4.4).

Table 4.1 is a summary of the water holding capacities (soil moisture levels when the soil is at Field capacity) of most New Zealand soil groups. This clearly shows that the field capacity of soils from a loessial origin can be very high. The storage of soil moisture at the colluvium/bedrock boundary allows for a consistent slow rate of recharge to bedrock aquifers principally during the winter months.

4.2.3 Barriers to Groundwater Movement

A summary of the perching lithologies observed in the Diamond Harbour area includes:

-tuff/ash beds (Plates 4.5, 4.6, and 4.7)
-tightly jointed or massive lavas
-highly weathered jointed lava masses
-volcaniclastic crater lake deposits
-lahar deposits (Plate 2.3)

Invariably some type of perching layer will be associated with the presence of volcanic bedrock springs. The Lyttelton Volcanics found in the upper Purau Valley consists of a major thickness (approximately 450m) of interbedded tuffs, agglomerates and volcanic conglomerates. These deposits represent a localized major barrier to deep percolating groundwater in the area. Many Lyttelton flows are also separated by thin layers of ash and laharic debris, which will act as perching layers to groundwater but are

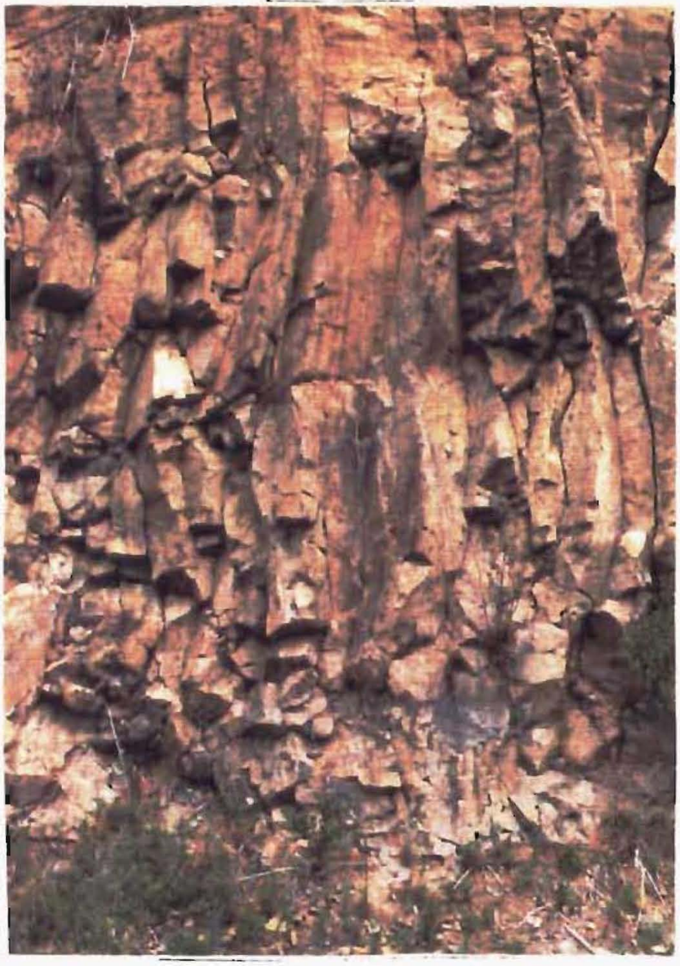


Plate 4.4 An outcrop of wavy regularly jointed Church Bay Olivine Basalt. (M36 GR 895304)

Plate 4.5 A good example of a perennial bedrock spring perched over a reddish ash horizon, upper Purau Valley. Flow is approx. 18 l/min during the summer of 1989. (N36 GR 902238)

Plate 4.6 Another example of a perennial bedrock spring. The perching horizon of reddish tuff is obvious in this exposure. Spring flow is existing from jointed lavas to the right of the photograph. (N36 GR 908242)

Plate 4.7 A perennial bedrock spring perched over a reddish tuff layer. The spring is clearly seen to exist from a rubbly lava flow above the base of the hammer. (N36 GR 904238)

Table 4.1 MEAN AVAILABLE WATER-HOLDING CAPACITIES OF SOIL GROUPS IN NEW ZEALAND
(From Standards Assoc. of N.Z., 1973)

Soil group	*Water available*			
	Millimetres per decimetre depth soil		*Inches per foot depth soil*	
	Depth from surface		*Depth from surface*	
	Up to 0·3 m	Below 0·3 m	Up to 12 in	Below 12 in
Northern yellow brown earths	17·5	11	2·1	1·3
Northern podzols and podzolized soils	22	9	2·6	1·1
Brown loams on basalt	13	7·5	1·6	0·9
Brown granular clays (North Auckland)	17·5	15	2·1	1·8
Brown granular loams (South Auckland)	18	7·5	1·9	0·9
Yellow brown loams	20	12	2·4	1·4
Yellow brown pumice soils	26	22	3·1	2·6
Central and Southern yellow brown earths	20	11	2·4	1·3
Yellow grey earths	22	11	2·6	1·3
Brown grey earths	18		2·2	
Organic soils (peat)	20 to 25	At least 20 to 25	2·4 to 3	At least 2·4 to 3

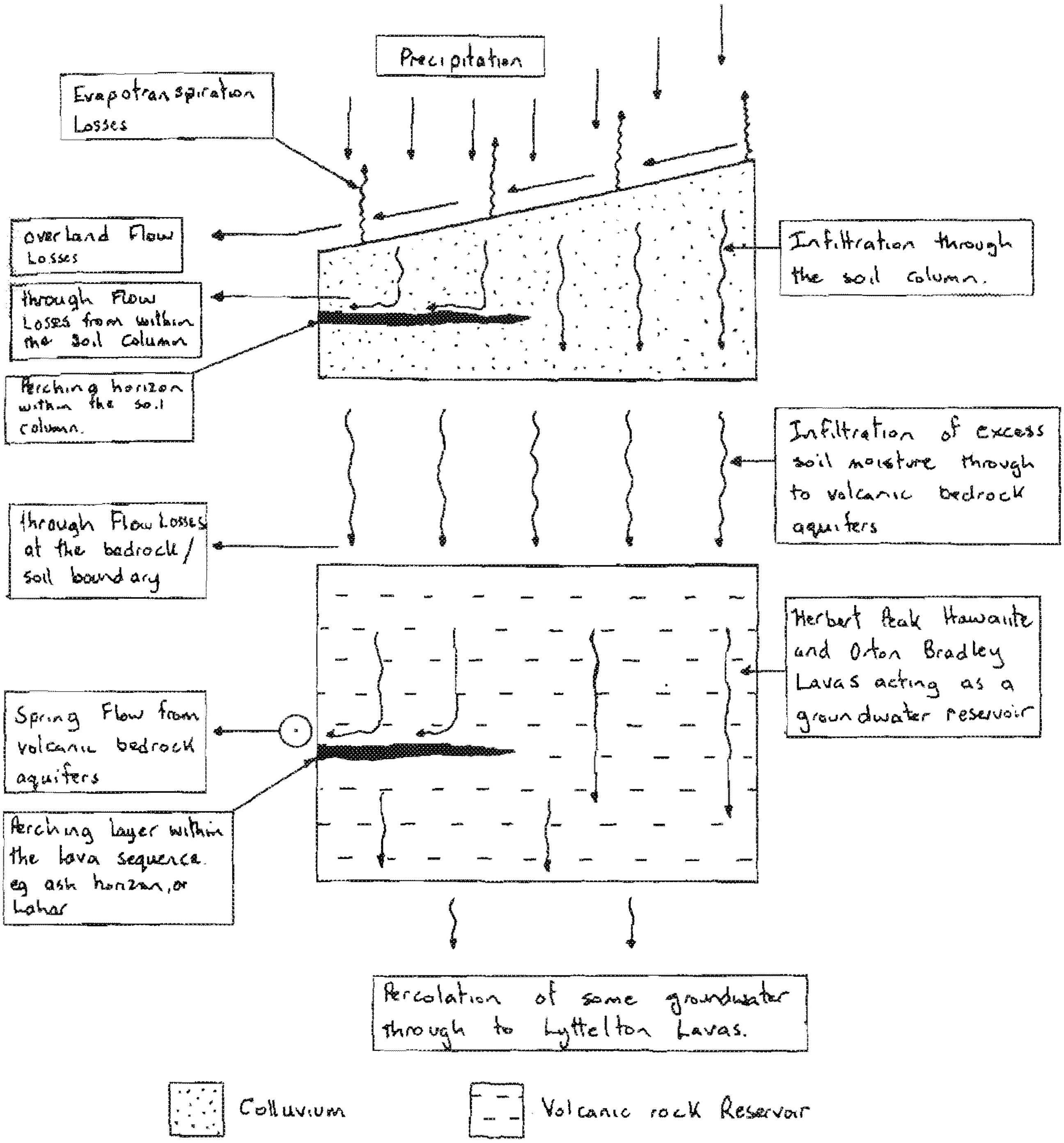


Fig. 4.4 Systems diagram showing the pathways of meteoric derived waters through regolith and bedrock systems in the High Altitude regions of Diamond Harbour.

often laterally discontinuous and may therefore only impede groundwater. Massive, poorly jointed Lyttelton lavas (ie jointing is only developed in some flows and can be infilled with weathering products), weathered lava rock masses and basal breccias are also seen to act as perching layers.

Associated with the Lyttelton Volcanic Group is a radial dike swarm with two centres; An older centre located in Head of the Bay (Lyttelton 1) and a younger centre in Charteris Bay (Lyttelton 2). These dikes appear to be trachytic in composition and a number are evident in the Lyttelton Volcanics in Purau Valley, but no evidence of dike-impounded groundwater could be seen and no springs could be specifically associated with the presence of these dikes. Occasional dikes are to be found in other volcanic formations, but unlike Hawaiian examples (see Appendix Seven), their influence on groundwater movement seems to be minimal.

The upper lavas of the Orton Bradley Formation are interbedded with frequent pyroclastic deposits, varying in thickness from 60 to 260m over a horizontal distance of 2.3km. Forming part of these pyroclastic deposits is a major tuff cone (70 to 260m in thickness) which underlies the lavas that form Mt Bradley in the upper Orton Bradley Valley. At least 20 springs are seen to exit from the lavas perched over these pyroclastics (Fig. 2.5).

More significantly, on the eastern side of the Orton Bradley Valley, and underlying part of the dip-slope, are the sediments of the Mt Bradley Volcaniclastic member which clearly act as a large, laterally extensive perching body to the overlying lava sequence. Major springs of high flow (ie 15 to 60 litres/minute) are seen to exit from lavas immediately overlying this member (eg, at M36 GR 880263). Occasionaly, springs are seen to emerge from large open fractures within the volcaniclastic member itself, although the origin of these fractures is unclear. Sewell (1985) notes that slumping of the lake deposits during deposition has formed some fractures within the volcaniclastic member, however this explanation is unlikely to explain other larger fractures found to be associated with springs. A possible explanation is that these are tensional fractures formed as a result of the doming of older sediments during the eruption of younger lavas.

Only minor thicknesses (<6m) of pyroclastic materials are found in the Herbert Peak Hawaiite lavas. Reddish tuff layers are often found separating lava flows, and these clearly act as perching layers to high altitude springs (Plates 4.5, 4.6, and 4.7). Thicknesses of up to 6m have been observed, but these layers are often laterally discontinuous over 100 to 200m. Small lahar deposits are also seen to act as perching layers within these lavas, and occasionally fractured pyroclastic beds within the Herbert Peak lavas are found to be exit points for bedrock springs.

4.3 A CURRENT MODEL FOR HIGH ALTITUDE SPRINGS

4.3.1 Seasonal Discharge Variability

Both Sanders (1986) and Namjou (1988) found that spring discharge showed seasonal trends. Peak flows tended to occur during the wettest months of the year (June to September), and were followed by low flows during the dry months of the year (October to March). It was reasonable to assume that recharge occurred mainly during the winter months, because little recharge would occur during the spring and summer months as most precipitation would be consumed by rapid plant growth and evaporation, leading to a decline in spring discharge. As rainfall increased through the autumn and winter months the moisture content of the surficial cover is replenished to beyond field capacity and water is made available for recharge to bedrock aquifers.

These observations were interpreted by Sanders (1986) to indicate that a "head"/storage-capacity model was appropriate to explain the behaviour of these springs.

Rainfall would recharge volcanic aquifers during the winter months resulting in an increase in hydraulic head and consequently an increase in spring discharge. As recharge declined during the spring through autumn months, the hydraulic head declines along with spring flow.

4.3.2 Storm Event Discharge Variability

Sanders (1986) noted that superimposed on the seasonal variability of spring flow was an 'event' variability. After significant rainfall spring discharge tended to increase, reaching a maximum two to six days after storm cessation and this was followed by a gradual decline until the next event (Fig. 4.5).

The time to peak flows was interpreted to depend on the antecedent wetness conditions existing in the catchment. When a volcanic rock reservoir is saturated to near its maximum capacity the vertical infiltration distance for 'new' event water decreases. Thus, the subsequent head increase and spring discharge increase is rapid. Sanders (1986) also noted that spring response to a storm event depended on local geology. The higher was the hydraulic conductivity of surficial materials the faster would be the through-put time of the recharge waters.

Sanders (1986) also noted that some local farmers had observed that during times of drought some dry springs would begin to flow again just before a rain event. Sanders' explanation for this was that a lowering of atmospheric pressure before the rain event had the effect of increasing the hydraulic head within the volcanic rock reservoir, thus the spring would begin to flow again.

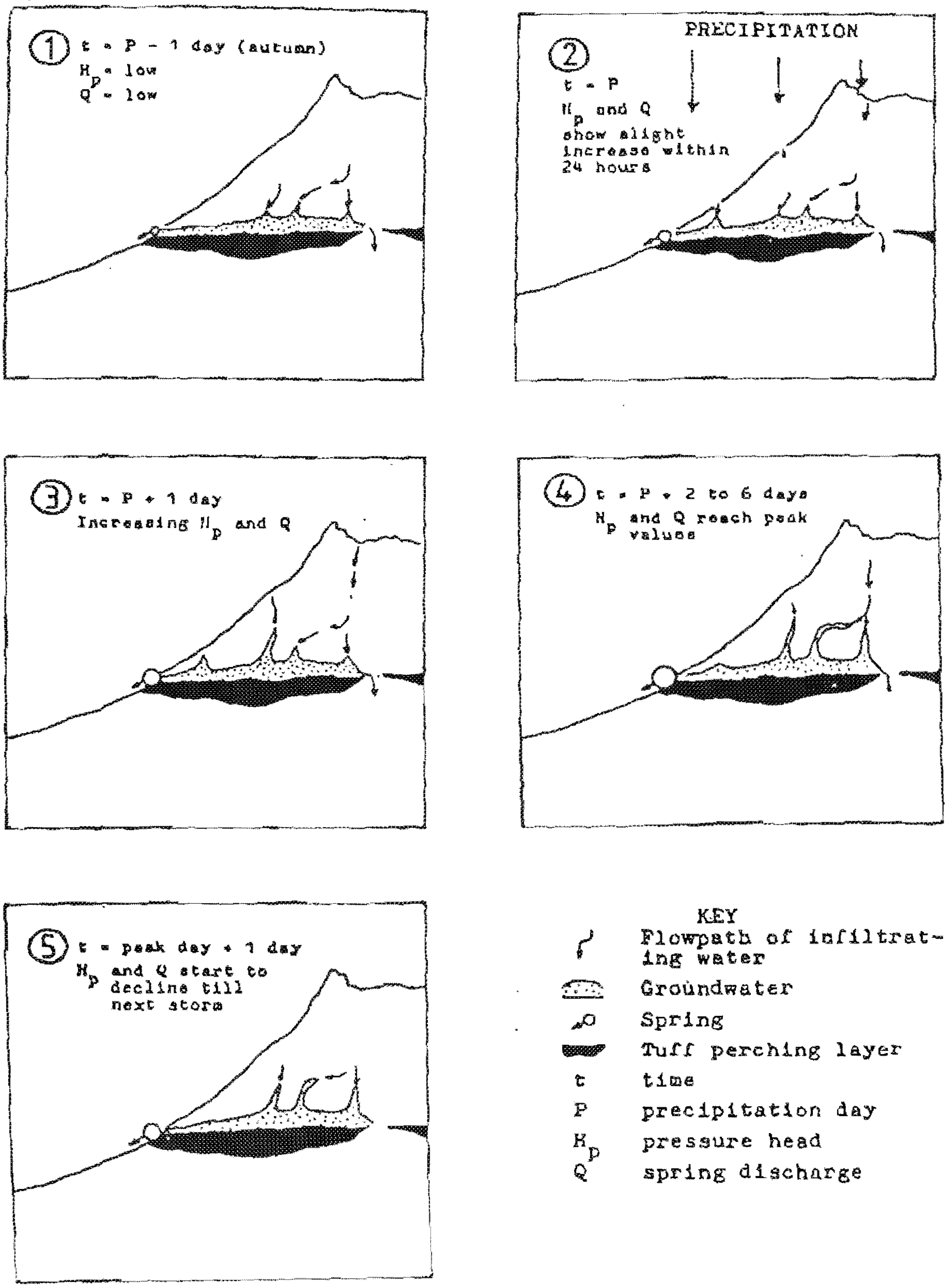


Fig. 4.5 Model to explain reponse of spring in summit region to storm events. Cartoons show schematic sections through heterogeneously jointed lavas containing a perched water body of irregular shape. (From Sanders, 1986)

4.3.3 Spring Flow Components

The observations described above led Sanders to the conclusion that spring discharge consisted of two components, viz 1) 'New' water from the current storm event which has moved by direct infiltration into the volcanic aquifer and subsequently discharged through the spring. This water was assumed to make a minor contribution to total flow and 2) 'Old' water, not related to the storm event stored within the volcanic rock reservior for up to 15 years, which was considered to make the major contribution to total spring flow during a storm event.

4.3.4 Recharge of Volcanic Springs

The studies of Sanders (1986) and Namjou (1988) indicate that a direct precipitation-infiltration-recharge model is appropriate for the volcanic springs examined in the course of their investigations. Oxygen-18 and Deuterium ratios for the various springs from the above studies plot close to the New Zealand Meteoric Water line (as defined by Stewart and Taylor, 1981):

viz $\delta D = 8.0\ \delta^{18}O + 13$, δ values are given in parts per thousand, $^{0}/_{00}$

where $\delta(^{0}/_{00}) = \left(\frac{R_{sample}}{R_{v\text{-}smov}} - 1\right) \times 1000$

Rv-smov = Standard Mean Ocean Water held at IAEA, Vienna

Figure 4.6 from Sanders (1986) shows that Akaroa spring waters are in good agreement with a direct precipitation-infiltration-recharge model. The responsiveness of spring discharge to storm events is also suggestive of this type of model.

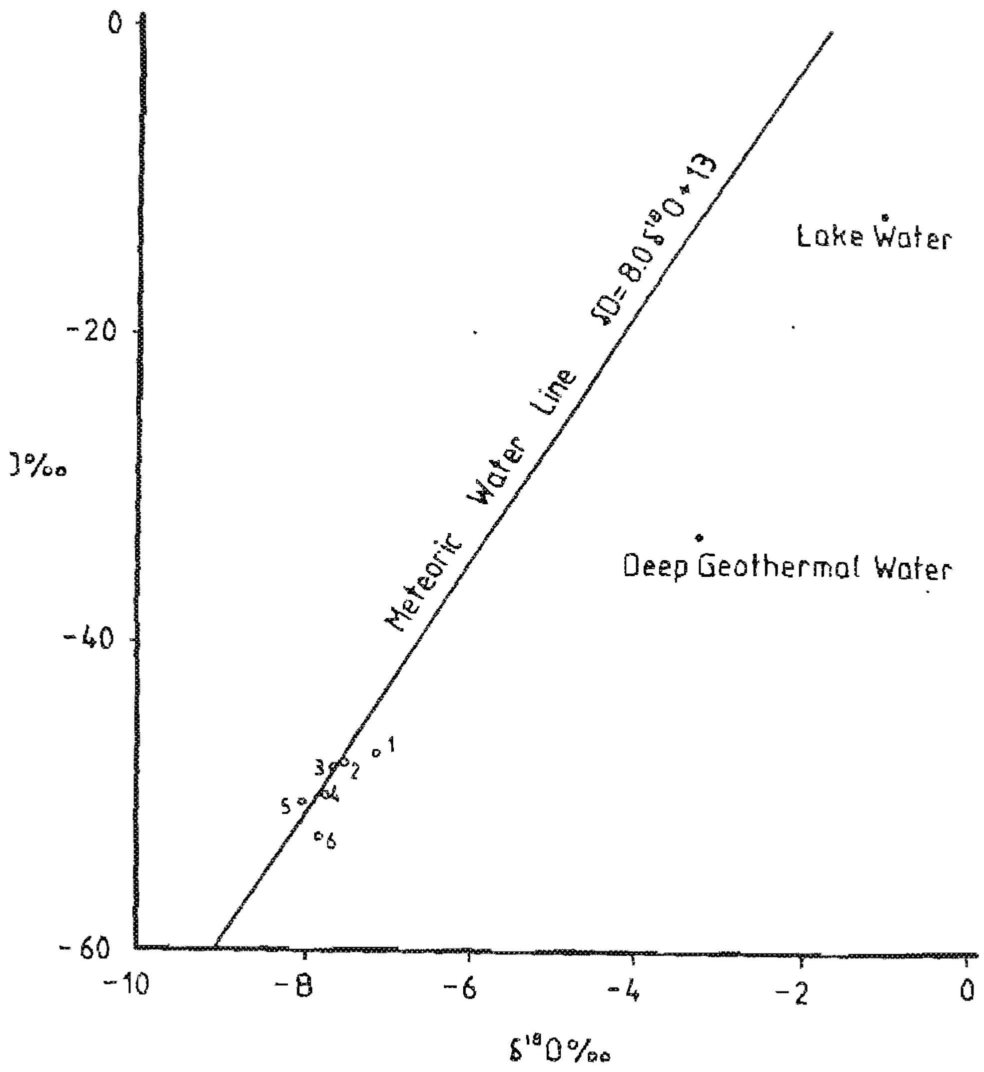


Fig. 4.6 Plot of deuterium and oxygen-18 contents for water samples taken at six Pigeon Bay Valley springs. Note the proximity of the samples to the N.Z. Meteoric Water Line. Lake water and deep geothermal samples are from Stewart and Taylor (1981) and are plotted for contrast. Sample numbers from Sanders (1986) are as follows:

1. Bull Paddock Spring
2. Top Pigeon Bay Spring
3. Starvation Gully Spring
4. Old Summit Road Spring
5. Top Glen Spring
6. Bottom Glen Spring

These interpretations can be related to spring permanence. The reservoirs for volcanic springs must vary in size, and where recharge is sufficient flow will be maintained in relation to the hydraulic head of the stored water. Where reservoir volumes are small and/or recharge does not occur, then hydraulic head falls along with spring discharge until the spring dries up.

Sanders accounts for the location and the high flows of springs near ridge tops by two factors, viz 1) the high rainfall and 2) the high infiltration rates for geological materials found in these areas. Sanders also made an estimate of annual recharge in the French Hill (Akaroa County) area based on a number of assumptions. He assumed that most recharge occurred during the winter and that 50% of this would be available to recharge. His calculations showed that up to $21m^3$ of recharge waters would be available for every $100m^2$ of ground surface on French Hill.

4.4 MT HERBERT SPRING DISCHARGE EXPERIMENT

4.4.1 Background

To test the model developed by Sanders (1986) an experiment was developed whereby the naturally occurring environmental isotope, oxygen-18, was sampled on a regular basis from one High Altitude spring. Two samples of the radioactive isotope, tritium, were also taken seven months apart (March and October 1988).

The field experiment was established around a known perennial spring X1a located within the Herbert Peak Hawaiite lavas of the upper Purau Valley (N36 GR 907239) (Fig. 4.7). The spring was selected principally because it could be seen that flow was exiting directly from a fractured lava flow overlying a reddish, moderately weathered ash layer, and secondly because it was a perennial spring. Relatively easy track access was also a

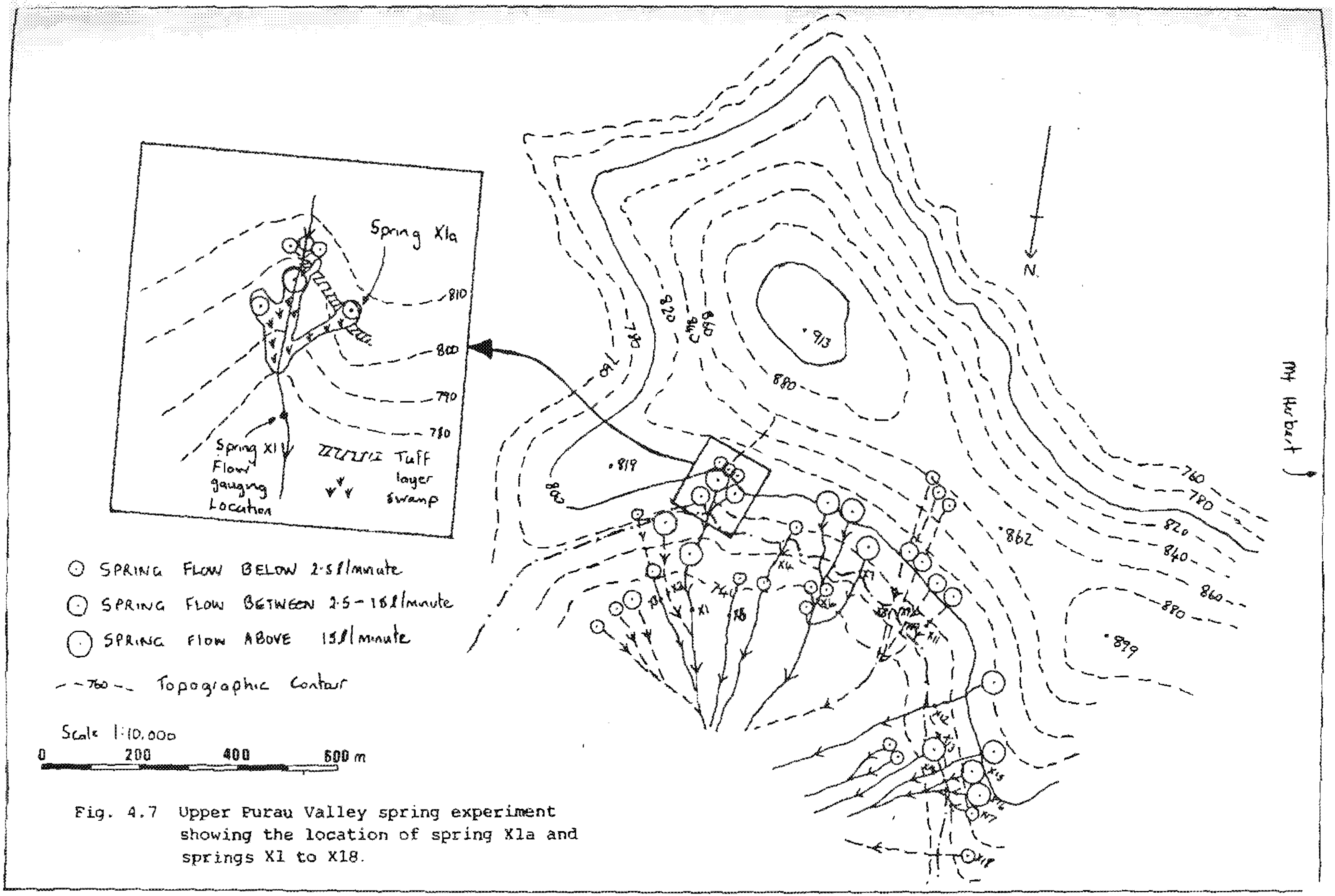


Fig. 4.7 Upper Purau Valley spring experiment showing the location of spring X1a and springs X1 to X18.

consideration, particularly as a lot of heavy equipment was needed at the site.

Figure 4.7 is a schematic diagram of the location of spring X1a, and several other bedrock springs also discharge into a small re-entrant that has been eroded into the volcanic bedrock. This has the effect ot channelling spring flow, overland flow and soil moisture flow to a point where it joins a tributary stream of the Purau river. These other springs also appear to exit from jointed, fractured lavas that are perched over similar pyroclastic beds. Capping the volcanics in the area is a mantle of mixed loess-volcanic colluvium estimated to be from 0.3 to 1.2m thick.

4.4.2 Experimental Layout

The entire flow from spring X1a was directed into a 44 gallon drum via a 5m section of PVC house guttering (Fig. 4.8 and Plates 4.8). The guttering was secured to the drum top by wire, and along its length a number of stakes prevented wind or snow from damaging the channel. The guttering was enclosed along its length by polythene sheeting to prevent spring water from being isotopically contaminated by 'new' rain or snow waters. A down pipe was attached to the guttering to direct flow into the drum so as to prevent water surface disturbance.

Attached to the 44 gallon drum was a calibrated mini 10:1 V-notch weir. An 80mm section of pipe connected the drum with the V-notch weir. Fixed to the top of the drum was a Belfort water level recorder which was operated by a wind-up seven day clock. A metal tape connected a float to the rotating wheel that operated the instrument's pen (Fig. 4.8 and Plate 4.8). Zero flow was recorded on the charts by allowing the drum to fill until just before flow began from the weir. Constant flow records were this obtained for a 34 day period from 27/7/88 to 16/9/88.

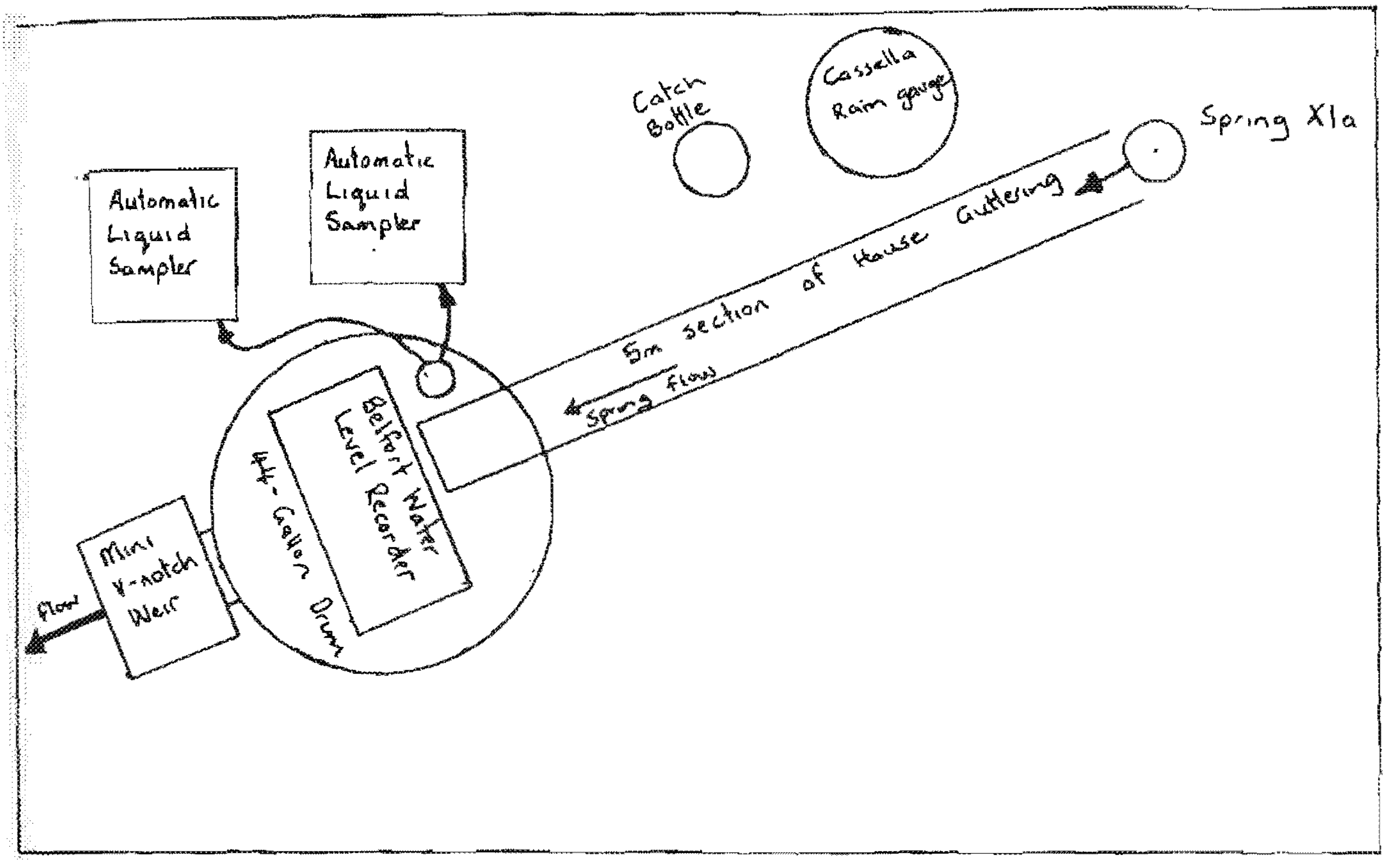


Fig. 4.8 Spring X1a experimental layout.

Plates 4.8 a and b. Spring X1a experimental layout, upper Purau Valley. (N36 GR 903238)

Two Automatic Liquid Samplers (ALS) were used to sample the spring water flowing through the drum. Each sampler had 24 bottles each with individual intake hoses. Initially the sampling period was set electronically for every eight hours, with one sampler offset from the other by four hours. This meant samples were taken every four hours for a total of eight days, after which samples needed to be collected. Later it was found that only daily samples needed to be taken as the oxygen-18 ratios were not changing significantly over a storm event.

To complete the experimental layout an automatic Cassella rain gauge was set-up adjacent to the spring to record precipitation. This instrument operated a seven day chart recorder. The gauge was located within 100m of the ridge top, and it was assumed measurements of precipitation would be representative of the local area. A catch bottle with attached funnel was used to collect precipitation samples. Lack of funding meant that daily atmospheric pressure readings from Christchurch airport had to be used for the experiment.

The whole area around the spring was fenced off to avoid stock damage. Charts and samples were collected once every seven days, or as soon as possible following a storm event to avoid evaporation of the precipitation sample from the catch bottle.

4.4.3 <u>Theoretical Basis for the Experiment</u>

Appendix Six gives a more detailed summary of the isotope theory involved in this experiment. Briefly, the writer hoped to use the environmental isotope oxygen-18 (^{18}O) to separate a spring hydrograph into its two possible components - 'old' stored groundwater and 'new' water derived from individual storm events. Various writers have noted that the fluctuations in spring flow observed for Banks Peninsula springs occur in response to storm events (eg Sanders, 1986), as discussed in section 4.4.

Before going further, it is necessary to clarify the possible origins of spring water in relation to the site where gauging occurs. This experiment involved a true bedrock spring, that is, the entire spring flow could be seen exiting from a fractured lava flow (Fig. 4.2). There was no possibility of any component of flow being derived from the soil moisture storage or from direct precipitation. Other writers have clearly shown that the origin of spring flow from some springs is in doubt because flow could have been derived from bedrock aquifers, soil moisture storage and/or direct precipitation into the channel.

In relation to the current experiment, the possible responses the spring could have to a storm event were as follows:

1) No response to precipitation. This was considered to be unlikely given the observations of other researchers, for example Sanders (1986) and Namjou (1988).

2) An increase in spring flow whereby the increased flow is derived from a mixture of 'old' stored water and newly infiltrated precipitation.

3) An increase in spring flow whereby the increased flow is derived entirely from 'old' stored water released by 'head' increase as a response to infiltration of 'new' water.

4) An increase in spring flow in response to changes in atmospheric pressure, with the increase in flow derived from 'old' stored water.

4.4.4 <u>Age Determination of Spring X1a Groundwater</u>

Two tritium measurements were taken from spring X1a in an attempt to determine the residence time of the spring water. Responses of hypothetical groundwater systems to the tritium input can be constructed by assuming that the total water discharged has a specified age distribution, where age is defined as the elapsed time since precipitation.

There are a wide range of possibilities in choosing age distributions for any particular point in a groundwater system. Where a number of measurements have been made from a particular system over a period of several years, the number of distributions can be reduced to only a few possibilities. In this case only two measurements were available, and clearly any age distribution arrived at is limited by this fact.

The most widely used theoretical concept is the exponential age distribution.

$$f(t) = \frac{1}{T} e^{-t/T}$$

where T is the mean residence time of a water molecule in the system. This system can apply to an aquifer system where waters are well mixed throughout, or where waters are not mixed throughout the aquifer but flow paths of different age unite at the output to yield this age distribution (Fig. 4.9). The other end member is the piston-flow model, where water moves through the aquifer as water moving through a pipe. There is no mixing of waters in a piston flow model and 'new' water flows in at one end while 'old' water flows out the other (Fig. 4.10).

Various combinations of these two extremes have been found useful in other studies of groundwater systems. Two simulated models representing the age distribution of the spring Xla groundwaters were developed by Dr M.K. Stewart (DSIR). The first has an exponential (or mixing) portion of the system which is three times the size of the piston (or non-mixing) portion of the model. This model predicts that groundwater with a tritium ratio of TR = 4.27 in March 1988

Fig. 4.9 RESPONSES OF SYSTEMS WITH EXPONENTIAL AGE DISTRIBUTION TO INPUT OF TRITIUM RECORDED IN KAITOKE PRECIPITATION
τ = mean residence time of a water molecule in the system
(From Taylor, 1987)

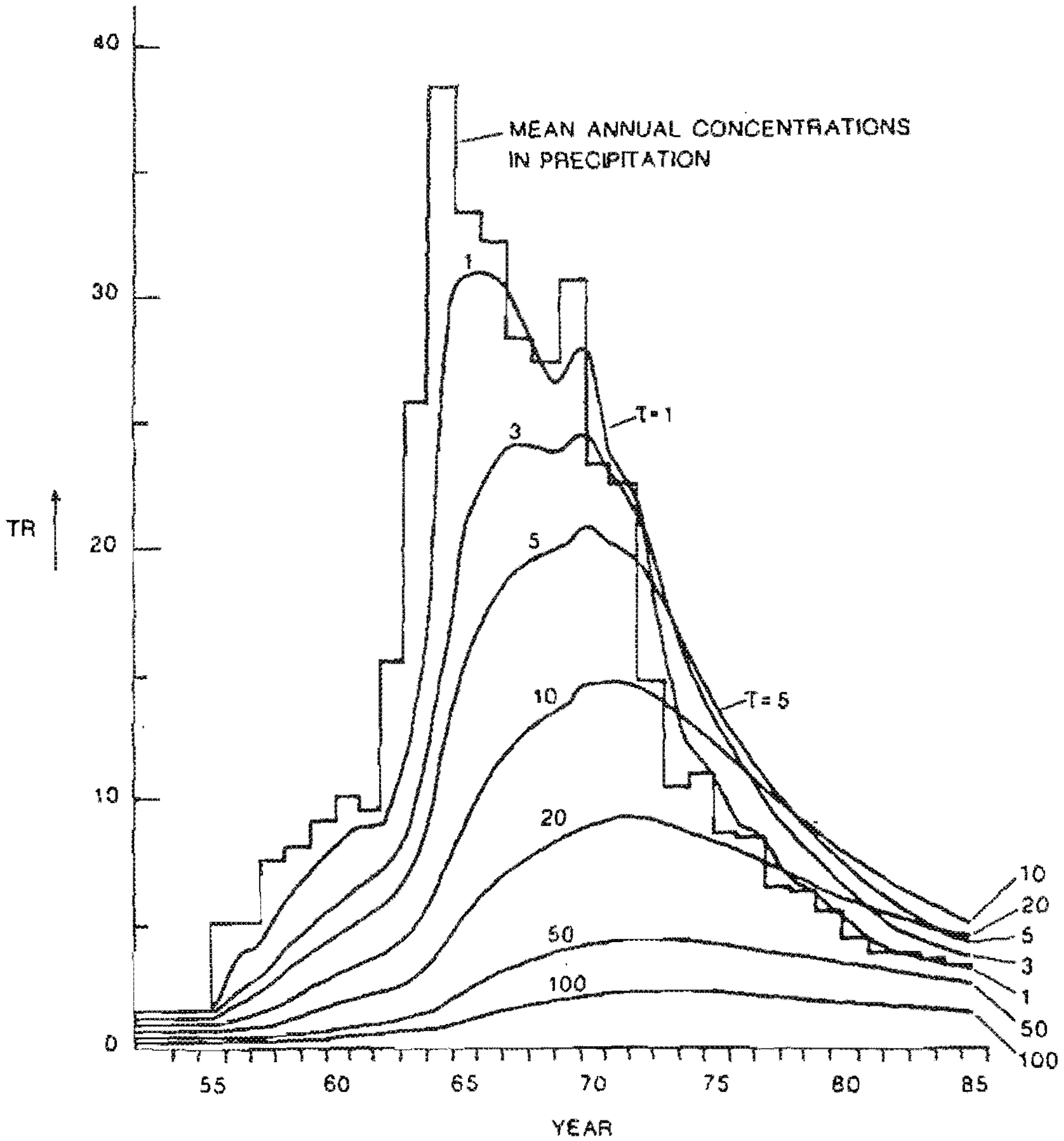
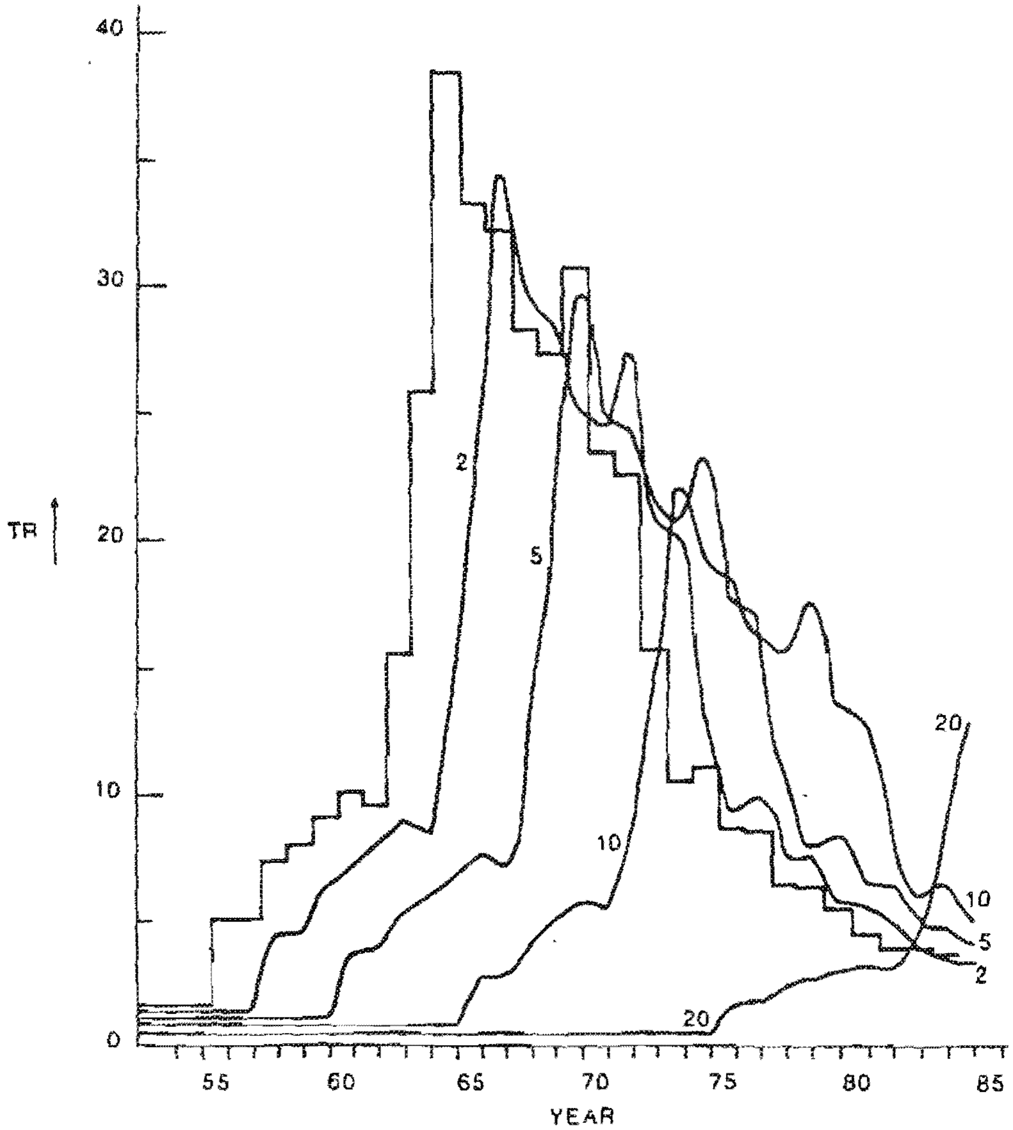


Fig. 4.10 RESPONSE OF AQUIFER WITH PISTON-FLOW CONDITION TO INPUT OF TRITIUM RECORDED AT KAITOKE

(SHOWN FOR FLOW-TIMES 2,5,10,20 YEARS)

τ = mean residence time of a water molecule in the system.

(From Taylor, 1987)



and TR = 4.05 in October 1988 would have a mean residence time of 10 to 25 years (M.K. Stewart, pers. com.). Tables 4.2 and 4.3 show simulated outputs for two types of models used in this study.

A wholly exponential model (ie an exponential model with no piston flow portion) predicts that groundwater would have a current maximum TR of 3.74 and would have a mean residence time of between 10 to 20 years. Clearly this value is lower than the two values of 4.27 and 4.05 gained for this spring. A wholly piston flow model predicts a mean age of 12 to 25 years for spring X1a groundwaters but this model does not represent the most likely geological model for the area.

The best fit for the field data was found using the exponential-piston flow model, and the lack of variation in Oxygen-18 data also suggests that either an exponential, or an expontential-piston flow, model is appropriate, with a large ratio of exponential volume to piston flow volume, (M.K. Stewart, pers. com.).

It seems likely, therefore, that the mean age of spring X1a groundwaters is between 10 and 25 years, which indicates that there is a considerable hold-up time for waters witin these lava flows.

4.4.5 Oxygen-18 Evidence for Spring Flow

Spring flow was initially sampled at four hourly intervals, but when it became obvious that there would be considerable mixing of groundwaters (from tritium data and geological information) it was decided to only analyse daily samples. Table 4.4 is a summary of the daily oxygen-18 data for a period of 34 days, and figure 4.11 summarizes of all spring data for 25 days. Spring flow has essentially no variation in oxygen-18 ratios over the period sampled, and has a range between -7.66 and -7.85 (a significant variation would have been a range over say 10 δO^{18} between

30-08-88

Table 4.2 Simulated system outputs for an
EXPONENTIAL-PISTON FLOW MODEL FOR ETA = 1.33 ; TRITIUM (E/P RATIO = 3)
(Compiled by M. Stewart DSIR)

YEAR	INPUT	OUTPUT FOR DIFFERENT MEAN RESIDENCE TIMES (YEARS)						
	pptn	2	5	10	15	20	30	50 years
1954-55	1.50	1.35	1.16	0.92	0.75	0.62	0.44	0.24
1955	5.00	2.96	1.16	0.92	0.75	0.62	0.44	0.24
1956	5.00	3.74	1.90	0.92	0.75	0.62	0.44	0.24
1957	7.30	5.19	2.44	1.29	0.75	0.62	0.44	0.24
1958	8.00	6.21	3.32	1.60	0.75	0.62	0.44	0.24
1959	9.00	7.17	4.10	2.09	0.98	0.62	0.44	0.24
1960	10.00	8.10	4.88	2.58	1.19	0.78	0.44	0.24
1961	9.40	8.27	5.66	3.08	1.52	0.93	0.44	0.24
1962	15.40	11.12	6.10	3.61	1.85	1.17	0.54	0.24
1963	25.70	17.26	7.69	3.98	2.20	1.42	0.62	0.24
1964	38.40	26.09	11.03	4.92	2.58	1.68	0.77	0.24
1965	33.20	27.99	16.14	6.79	2.86	1.96	0.92	0.24
1966	32.10	28.41	18.75	9.67	3.51	2.18	1.08	0.24
1967	28.20	26.82	20.40	11.51	4.76	2.66	1.26	0.29
1968	27.30	25.63	20.78	12.92	6.70	3.58	1.40	0.33
1969	30.60	26.57	20.85	13.67	8.02	4.99	1.69	0.40
1970	23.30	23.66	21.61	14.20	9.10	5.99	2.25	0.47
1971	22.50	21.88	20.61	14.99	9.77	6.82	3.10	0.54
1972	14.60	17.37	19.72	14.87	10.29	7.38	3.73	0.63
1973	10.30	13.20	17.39	14.69	10.95	7.82	4.27	0.70
1974	10.90	11.44	14.79	13.70	11.04	8.38	4.65	0.84
1975	8.50	9.48	13.04	12.43	11.07	8.52	4.97	1.10
1976	8.40	8.48	11.25	11.44	10.56	8.60	5.35	1.51
1977	6.31	7.04	9.94	10.37	9.83	8.31	5.49	1.81
1978	6.20	6.28	8.54	9.47	9.24	7.84	5.59	2.08
1979	5.33	5.51	7.51	8.51	8.57	7.46	5.47	2.28
1980	4.33	4.68	6.57	7.70	7.98	7.00	5.23	2.44
1981	3.77	4.01	5.68	6.94	7.33	6.59	5.04	2.64
1982	3.78	3.69	4.92	6.20	6.76	6.13	4.79	2.73
1983	3.53	3.42	4.37	5.53	6.21	5.72	4.57	2.80
1984	3.26	3.17	3.92	4.98	5.66	5.32	4.31	2.77
1985	2.98	2.91	3.53	4.50	5.15	4.91	4.07	2.68
1986	2.85	2.73	3.19	4.07	4.72	4.52	3.83	2.61
1987-27	2.70	2.57	2.92	3.68	4.32	4.18	3.59	2.51
1988	2.55	2.43	2.69	3.35	3.96	3.87	3.35	2.42
1989	2.45	2.31	2.49	3.06	3.62	3.58	3.14	2.31
1990	2.35	2.21	2.33	2.80	3.33	3.31	2.94	2.21
1991	2.25	2.11	2.18	2.58	3.06	3.06	2.75	2.10
1992	2.15	2.02	2.06	2.38	2.82	2.84	2.57	1.99
1993	2.10	1.95	1.95	2.21	2.61	2.63	2.40	1.88
1994	2.00	1.87	1.86	2.06	2.41	2.45	2.25	1.78
1995	1.90	1.79	1.77	1.92	2.24	2.28	2.11	1.68
1996	1.85	1.72	1.69	1.80	2.08	2.12	1.97	1.59
1997	1.80	1.67	1.62	1.69	1.94	1.98	1.85	1.50
1998	1.75	1.62	1.55	1.60	1.82	1.85	1.74	1.42
1999	1.70	1.57	1.50	1.51	1.70	1.73	1.63	1.34
2000	1.65	1.52	1.45	1.44	1.59	1.62	1.54	1.27

Predicted tritium ratios

Extrapolated values

30-08-88

Table 4.3 Simulated system outputs for a
PISTON FLOW MODEL: TRITIUM (Compiled by M. Stewart DSIR)

YEAR	INPUT ppln	OUTPUT FOR DIFFERENT FLOW TIMES (YEARS) 2	5	10	15	20	30	50 years	
1954-55	1.50	1.34	1.14	0.86	0.65	0.49	0.28	0.09	predicted tritium ratios
1955	5.00	1.34	1.14	0.86	0.65	0.49	0.28	0.09	
1956	5.00	1.34	1.14	0.86	0.65	0.49	0.28	0.09	
1957	7.30	4.47	1.14	0.86	0.65	0.49	0.28	0.09	
1958	8.00	4.47	1.14	0.86	0.65	0.49	0.28	0.09	
1959	9.00	6.53	1.14	0.86	0.65	0.49	0.28	0.09	
1960	10.00	7.16	3.78	0.86	0.65	0.49	0.28	0.09	
1961	9.40	8.05	3.78	0.86	0.65	0.49	0.28	0.09	
1962	15.40	8.94	5.52	0.86	0.65	0.49	0.28	0.09	
1963	25.70	8.41	6.05	0.86	0.65	0.49	0.28	0.09	
1964	38.40	13.77	6.81	0.86	0.65	0.49	0.28	0.09	
1965	33.20	22.99	7.57	2.86	0.65	0.49	0.28	0.09	
1966	32.10	34.35	7.11	2.86	0.65	0.49	0.28	0.09	
1967	28.20	29.70	11.65	4.18	0.65	0.49	0.28	0.09	
1968	27.30	28.71	19.45	4.58	0.65	0.49	0.28	0.09	
1969	30.60	25.22	29.06	5.15	0.65	0.49	0.28	0.09	
1970	23.30	24.42	25.12	5.73	2.17	0.49	0.28	0.09	
1971	22.50	27.37	24.29	5.38	2.17	0.49	0.28	0.09	
1972	14.60	20.84	21.34	8.82	3.16	0.49	0.28	0.09	
1973	10.30	20.13	20.66	14.71	3.47	0.49	0.28	0.09	
1974	10.90	13.06	23.15	21.99	3.90	0.49	0.28	0.09	
1975	8.50	9.21	17.63	19.01	4.33	1.64	0.28	0.09	
1976	8.40	9.75	17.03	18.38	4.07	1.64	0.28	0.09	
1977	6.31	7.60	11.05	16.15	6.67	2.39	0.28	0.09	
1978	6.20	7.51	7.79	15.63	11.13	2.62	0.28	0.09	
1979	5.33	5.64	8.25	17.52	16.64	2.95	0.28	0.09	
1980	4.33	5.55	6.43	13.34	14.38	3.28	0.28	0.09	
1981	3.77	4.77	6.36	12.88	13.91	3.08	0.28	0.09	
1982	3.78	3.87	4.77	8.36	12.22	5.05	0.28	0.09	
1983	3.53	3.37	4.69	5.90	11.83	8.43	0.28	0.09	
1984	3.26	3.38	4.03	6.24	13.26	12.59	0.28	0.09	
1985	2.98	3.16	3.28	4.87	10.09	10.88	0.94	0.09	
1986	2.85	2.92	2.85	4.81	9.75	10.52	0.94	0.09	
1987-88	2.70	2.67	2.86	3.61	6.33	9.24	1.37	0.09	
1988	2.55	2.55	2.67	3.55	4.46	8.95	1.50	0.09	Extrapolated values
1989	2.45	2.42	2.47	3.05	4.72	10.03	1.69	0.09	
1990	2.35	2.28	2.25	2.48	3.68	7.64	1.88	0.09	
1991	2.25	2.19	2.16	2.16	3.64	7.38	1.76	0.09	
1992	2.15	2.10	2.04	2.16	2.73	4.79	2.89	0.09	
1993	2.10	2.01	1.93	2.02	2.69	3.38	4.82	0.09	
1994	2.00	1.92	1.85	1.87	2.31	3.57	7.21	0.09	
1995	1.90	1.88	1.78	1.71	1.88	2.79	6.23	0.09	
1996	1.85	1.79	1.70	1.63	1.63	2.75	6.03	0.09	
1997	1.80	1.70	1.63	1.55	1.64	2.07	5.29	0.09	
1998	1.75	1.65	1.59	1.46	1.53	2.03	5.12	0.09	
1999	1.70	1.61	1.51	1.40	1.41	1.75	5.74	0.09	
2000	1.65	1.57	1.44	1.35	1.29	1.42	4.37	0.09	

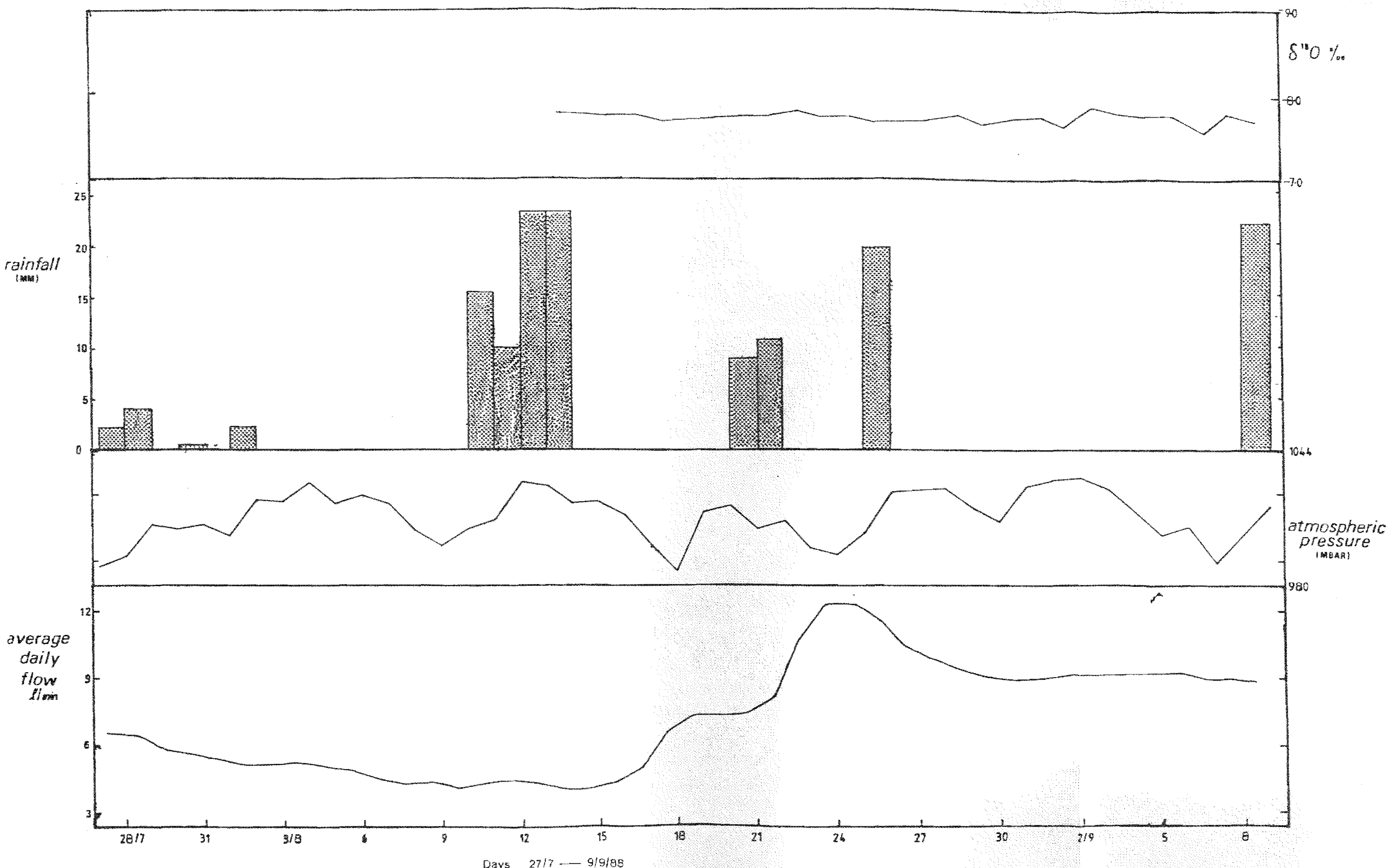


Fig. 4.11 Plot of average daily spring flow from spring Xla against daily atmospheric pressure readings, rainfall and oxygen-18 data for the period 27/7/88 to 9/9/88.

pre-event spring water and post-event spring water). Re-analysis of samples taken on the 5/9 and 6/9/88 brings these values more in line with the general trend of oxygen-18 results (ie there being essentially no day to day variation).

In general, oxygen-18 values remain very constant and this lack of variation (most likely since at least March 1988, (M.K. Stewart, pers. com.)) indicates considerable average residence time and the mixing of waters of different ages (based on an exponential-piston flow model which best fits the age distribution of these waters). Stable isotopic evidence, as a result, supports the radioactive isotopic evidence outlined in section 4.4.4, that a well mixed reservoir system exists for this spring and that the spring water has considerable average residence time.

The initial aims of this experiment were to determine the age distribution of spring X1a groundwaters, and to separate the spring hydrograph into its component parts, ie 'new' and 'old' waters. If the oxygen-18 data had showed a significant variation (a difference of at least 10 $^{o}/_{oo}$ between the $\delta^{18}O$ values of pre-storm event and post-storm event spring flow) then it could be shown that spring flow did include a component of 'new' storm event water. However, as there was essentially no variation in oxygen-18 results there was no need to look further at hydrograph separation. Most storm events had oxygen-18 values between -7.33 and -7.63 (Table 4.5). Only one event showed an oxygen-18 value significantly different from spring baseflow (-11.58 for an event on the 22/8/88). This value was considered too close to the δO^{18} values of the pre-event spring water to result in any obvious change in post-event δO^{18} spring water values (assumming the increased spring flow included 'new' water), and therefore hydrograph separation techniques could not be applied (Fig 4.11).

The oxygen-18 values gained for this experiment (see table 4.5) were found to be typical of Banks Peninsula

Date	$\delta^{18}O‰$
13/8	-7.78
14/8	-7.78
15/8	-7.76
16/8	-7.76
17/8	-7.69
18/8	-7.71
19/8	-7.73
20/8	-7.76
21/8	-7.76
22/8	-7.81
23/8	-7.74
24/8	-7.73
25/8	-7.66
26/8	-7.69
27/8	-7.70
28/8	-7.77
29/8	-7.67
30/8	-7.74
31/8	-7.76
1/9	-7.65
2/9	-7.85
3/9	-7.80
4/9	-7.76
5/9	-7.78
6/9	-7.58
7/9	-7.78
8/9	-7.70
9/9	-7.71
10/9	-7.70
11/9	-7.69
12/9	-7.74
13/9	-7.70
14/9	-7.72
15/9	-7.71
16/9	-7.68

Table 4.4 $\delta^{18}O$ Data for Spring XIa, August - September, 1988

Precipitation Event (Date)	Oxygen-18 Ratio
13/8/88	-7.63
20/8 to 21/8/88	-11.58
25/8/88	-7.33
8/9/88	-7.47

Table 4.5 Oxygen-18 Analyses for Rainfall Events

spring groundwaters precipitated at moderate altitude (M.K. Stewart, pers. com.). On the basis of stable isotopic and the radioactive evidence discussed in section 4.4.4, it is concluded that the entire flow from bedrock spring X1a following a storm event is 'old' water, and that there is no component of 'new' groundwater added to the increased spring discharge. Thus, some other mechanism of increasing spring discharge must be found to explain this response to storm events.

4.4.6 Calculation of Reservoir Size

It now becomes possible to estimate the size of the volcanic groundwater reservoir located in the upper Purau Valley on the basis of known flow records (Appendix 11), an estimation of the total rock volume in the area, and a known age distribution of the groundwaters from a selected spring (X1a). The total volume of rock that would provide the reservoir for springs X1 to X18 (Fig. 4.7) is approximately 50×10^6 m^3 (Appendix 11). The median flow of all springs that drain this rock volume is calculated to be $295 m^3$/day over the period June 1987 to June 1988 (Appendix 11). Assuming that the residence time of spring X1a is typical of all springs on this slope, then an approximation of the volcanic reservoir size in the upper Purau Valley is between 1×10^6 m^3 and 2.6×10^6 m^3. These figures are based on an approximation of mean residence times varying from 10 to 25 years (see section 4.4.4), and the groundwater reservoir volumes represent between 2 and 5% of the total volume of volcanic rock present in the upper Purau valley in the vicinity of spring X1a (Fig. 4.7).

Similar calculations for spring X1a suggest that at a median flow of 7.4 l/min (over the period 27/7/88 to 16/9/88), and assuming a residence time of between 10 and 25 years, a reservoir of between $39,000 m^3$ and $97,000 m^3$, is required for this spring alone. These volumes represent about 4% of the total calculated reservoir size (Appendix 11).

4.4.7 Atmospheric Pressure Effects on Spring Flow

Changes in atmospheric pressure can cause fluctuations in the hydraulic head of wells that penetrate confined aquifers (Davis and DeWeist, 1966). This relationship between atmospheric pressure and hydraulic head has also been observed in relation to the flow of springs. Where this relationship exists, a decrease in atmospheric pressure would result in an increase in spring discharge, and vice versa.

Figure 4.11 shows the relationship found between atmospheric pressure (measured at Christchurch airport) and spring X1a flow records. There are several distinctive periods of low atmospheric pressure and these do not appear to coincide with any marked changes in spring discharge magnitude. It is reasonable to assume then that spring X1a exits from an unconfined aquifer, and that no obvious relationship between spring flow and atmospheric pressure exists for this spring. To confirm this conclusion, local atmospheric pressure observations should have been used with a longer flow record, but this was not possible due to financial limitations.

Possible explanations for both Sanders' observations and the evidence from this study are 1) that the local farmers observations were inaccurate, or 2) that both confined and unconfined volcanic rock aquifers exist on Banks Peninsula. The writer believes the latter explanation is probably correct.

4.4.8 The Storm Event Variability of Spring X1a

Figure 4.11 presents a summary of the data from the spring experiment. From the 27/7 to the 3/8/88 three rain events of under 5mm occurred, and there was no obvious spring flow response to these minor events. Between the 10/8 and 13/8/88 approximately 65mm of snow fell, and from the 16/8/88 there began a noticeable increase in spring discharge. Unfortunately the response time of the spring cannot be accurately deduced because in this case it depended on the rate of snow melt. A further 20mm or so of snow fell on the 20/8 and 21/8/88, and in response to this event spring discharge showed an even more marked increase. Peak flow for spring X1a over the monitored period was reached on about the 24/8/88, and despite a rain event of about 20mm on the 25/8/88, a decline in flow continued until a base level of flow around 9 litres/minute was established. Before the first major storm event on 10/8 - 13/8/88, base flow had declined to about 4 litres/minute. The final rain event of about 23mm shown in Figure 4.11 occurred on the 8/9/88, and again spring flow did not show any noticeable increase above the new higher base flow level.

Spring X1a clearly shows the storm event variability referred to by Sanders (1986). A flow magnitude variability of 128% was calculated for this spring over the period 27/8/88 to 9/8/88 (see section 4.5.2 for a definition of spring flow variability). It has been difficult to precisely determine the response time of this spring to individual events because two of the largest events which caused an increase in spring flow fell as snow. The subsequent slow snow melt process was presumably responsible for the increase in spring flow. Despite the fact that these events fell as snow, it has been shown that the bedrock spring X1a responded by an increase in flow within 72 hours for the event 10/8 - 13/8/88 and within 24 hours for the event 20/8 - 21/8/88. As the guttering that channelled the spring flow into the 44-gallon drum was covered it was impossible for any snow melt to have 'contaminated' the flow direct from the bedrock aquifer. If isotopic 'contamination' had occurred, and assumming the SO^{18} ratio of the rain event was significantly different to the spring baseflow, then a noticeable change in the spring δO^{18} ratio would have been observed in Figure 4.11.

The isotopic and flow information (Fig. 4.11) indicate that a "head"/storage capacity model, first suggested by Sanders (1986), is consistent with the results of this study. The recharge component of individual events causes an increase in hydraulic head within the aquifer system and results in an increase in spring flow. A more detailed analysis of this model for volcanic springs is presented later in this chapter.

4.4.9 Water Balance Calculations for Upper Purau Valley: 18/8/88 to 8/9/88

Table 4.6 shows a continuation of the water balance calculations made for the entire Purau catchment given in Chapter Three. Table 4.6 calculations relate specifically to the upper Purau Valley area where springs X1 through X18 are located (Fig. 4.7). An attempt has been made to calculate an artificial flow record total for this set of springs, based on the constant flow record of spring X1a (Appendix 11). The aim of this exercise was to determine over the specified period (18/8/88 - 8/9/88) the approximate quantity of water lost to recharge the volcanic rock reservoir that feeds these springs, and to determine how much rainfall is lost as quickflow. The assumptions that form the basis of this section are detailed in Appendix nine.

Of the total 121mm of precipitation that fell over the period 18/8 - 8/9/88, a surplus of approximately 89mm was made available for recharge to the volcanic rock reservoir (Table 4.6), and this represents a volume of approximately 73,000m^3 of water. Assuming the total reservoir volume is between 1,000,000m^3 and 2,600,000m^3, the amount of recharge to the system represents between approximately 3 and 7% of the total reservoir size over the specified period.

These figures are themselves indicators of the sensitivity of volcanic bedrock springs to rainfall. When a surplus of water in the soil profile exists (ie during

Date (1988)	Rainfall (mm)	T_f (mm)	Q_f (mm)	AET (mm)	$P-Q_f$ (mm)	SM (mm)	ΔSM (mm)
						+15.88	+12.85
10/8	14	0.28	0.01	1.14	13.99	+28.75	+7.83
11/8	9	0.29	0.03	1.14	8.97	+36.30	+19.77
12/8	21	0.35	0.09	1.14	20.91	+56.37	+19.78
13/8	21	0.34	0.08	1.14	20.92	+76.24	-1.14
14/8	-	0.26	-	1.14	-	+75.1	-1.14
15/8	-	0.28	0.02	1.14	-	+73.96	-1.16
16/8	-	0.32	0.09	1.14	-	+72.80	-1.37
17/8	-	0.42	0.23	1.14	-	+71.43	-1.43
18/8	-	0.46	0.29	1.14	-	+70.00	-1.44
19/8	-	0.47	0.30	1.14	-	+68.56	+6.53
20/8	8	0.49	0.33	1.14	7.67	+75.09	+8.48
21/8	10	0.53	0.38	1.14	9.62	+83.57	-1.75
22/8	-	0.68	0.61	1.14	-	+81.82	-1.89
23/8	-	0.78	0.75	1.14	-	+79.92	-1.89
24/8	-	0.78	0.75	1.14	-	+78.04	+16.17
25/8	18	0.74	0.69	1.14	17.31	+94.71	-1.80
26/8	-	0.72	0.66	1.14	-	+92.41	-1.73
27/8	-	0.67	0.59	1.14	-	+90.68	-1.68
28/8	-	0.63	0.54	1.14	-	+89.00	-1.63
29/8	-	0.60	0.49	1.14	-	+87.37	-1.59
30/8	-	0.58	0.45	1.14	-	+85.78	-1.60
31/8	-	0.58	0.46	1.14	-	+84.18	-1.93
1/9	-	0.61	0.50	1.43	-	+82.25	-1.92
2/9	-	0.60	0.49	1.43	-	+80.33	-1.93
3/88	-	0.61	0.50	1.43	-	+78.40	-1.93
4/9	-	0.61	0.50	1.43	-	+76.47	-1.93
5/9	-	0.61	0.50	1.43	-	+74.54	-1.93
6/9	-	0.60	0.50	1.43	-	+72.61	-1.92
7/9	-	0.06	0.49	1.43	-	+70.69	+18.08
8/9	20	0.60	0.49	1.43	19.51	+88.77	

Table 4.6 Water Balance Calculations for the Upper Puraù Valley

where T_f = Total flow, Q_f = Quickflow, AET = Actual Evapotranspiration, SM = Soil Moisture Level and ΔSM = Change in soil Moisture Level.

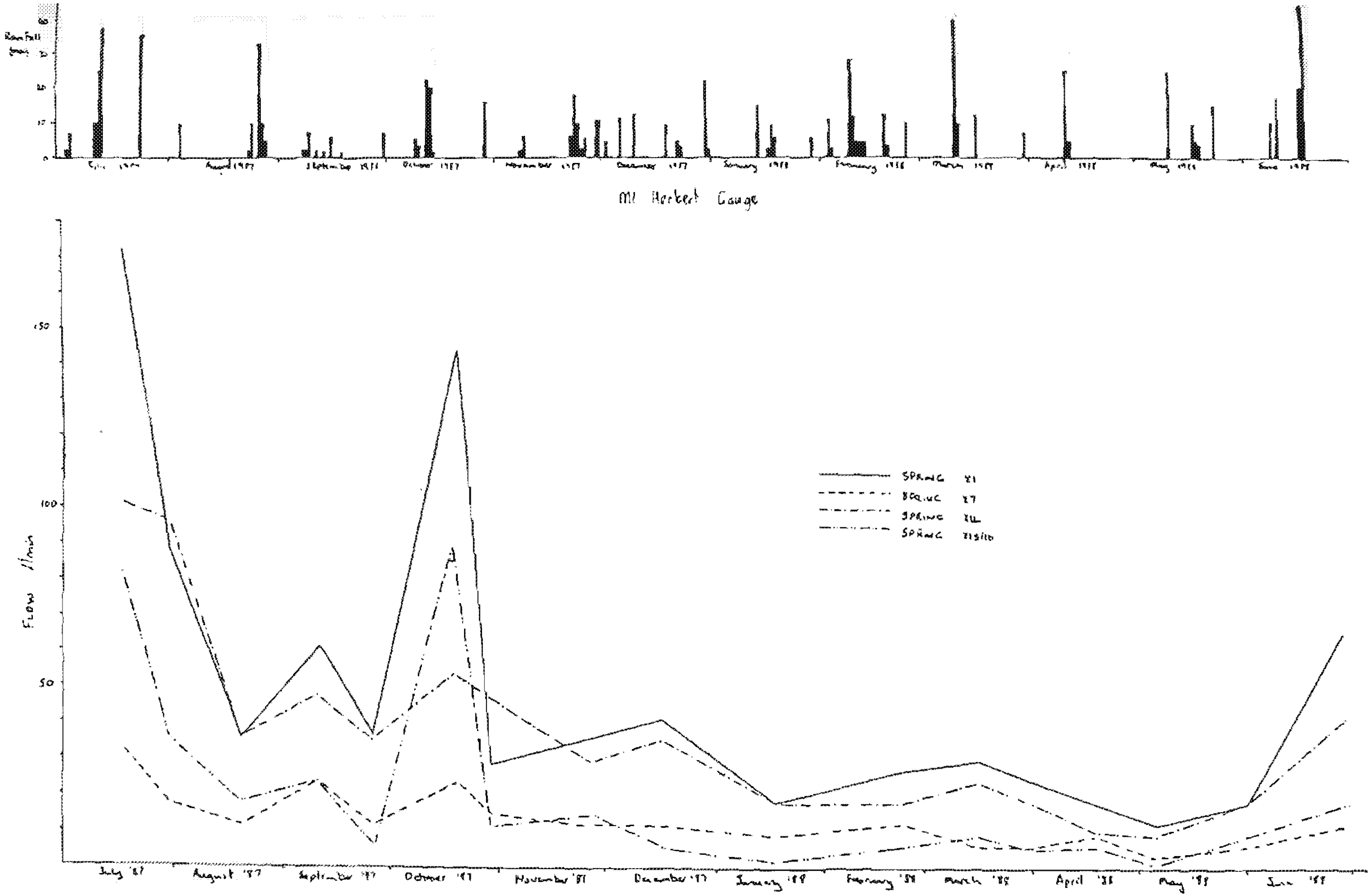


Fig. 4.12 Annual Flow record of 4 High Altitude Springs, upper Purau Valley.

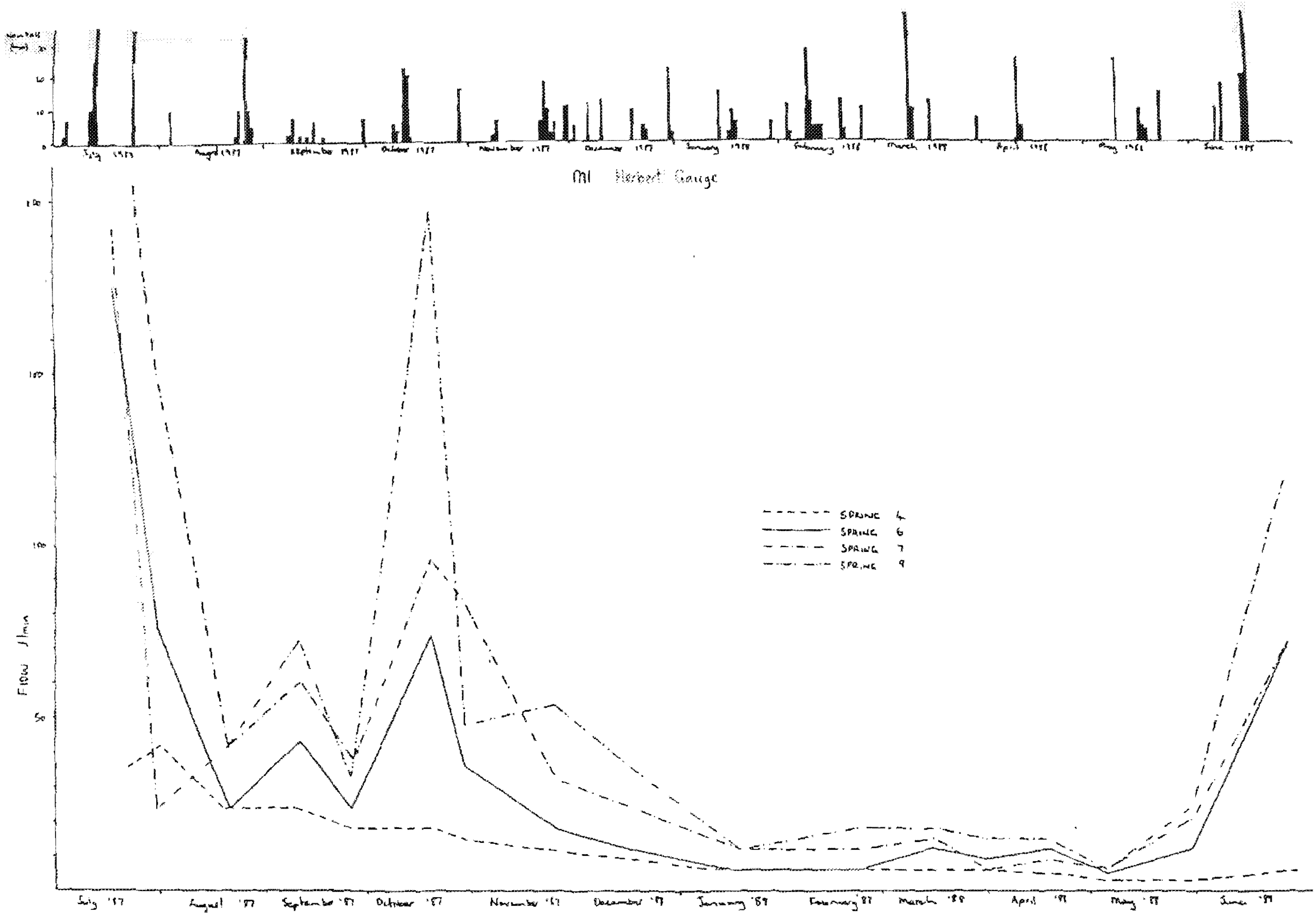


Fig. 4.13 Annual Flow Record of 4 High Altitude Springs, upper Purau Valley.

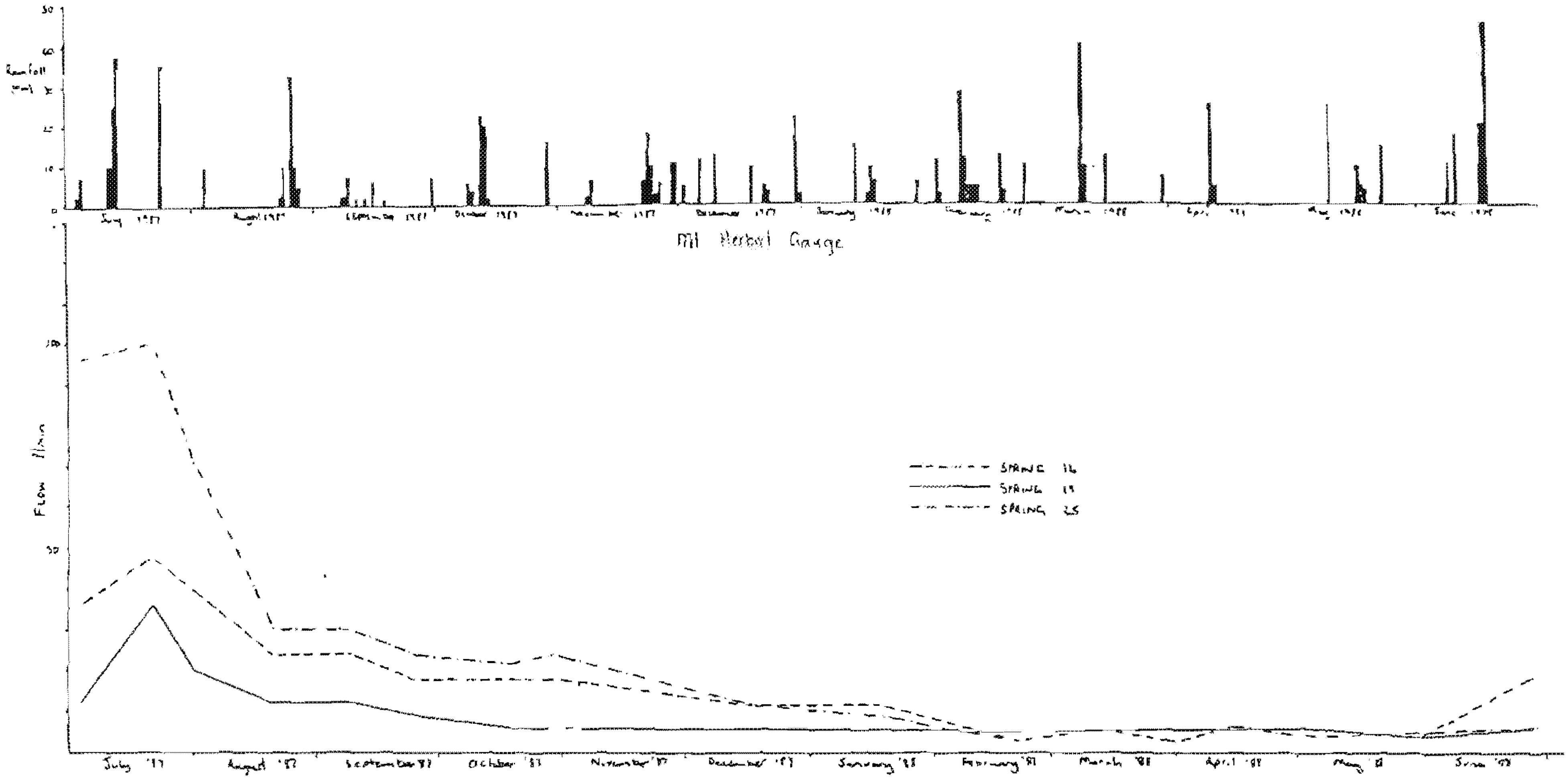


Fig. 4.14 Annual flow record of 3 High Altitude Springs, upper Orton Bradley Valley.

winter months when most recharge occurs) even a small rain event will be sufficient to add recharge to the reservoir and so produce a corresponding increase in spring flow. However, when a soil moisture deficit exists within the soil column (usually during the summer months) then small rain events will be absorbed to reduce the deficit and it would require a very large event before any water would be made available to recharge volcanic rock aquifers. The soil moisture surplus of about 16mm that existed on the 10/8/88 was insufficient to cause an increase in hydraulic head within the bedrock aquifers and a subsequent increase in spring flow. The soil moisture surplus was increased to about 76mm on the 13/8/88 and it was from this point on that spring flow began to increase. It would seem that a soil moisture surplus of around 75mm is required before an increase in hydraulic head within the volcanic aquifers occurs, which will then result in an increase in bedrock spring flow. It is not possible to say whether this figure is applicable to other springs, but the it will form a useful starting point for future analysis of Banks Peninsula High Altitude springs.

4.5 SPRING DISCHARGE MAGNITUDE AND VARIABILITY

4.5.1 Discharge Magnitude

Figures 4.12 to 4.14 show seasonal discharge magnitudes during the period June 1987 to June 1988 for 12 monitored springs or small sub-catchments. These springs were monitored on either a fortnightly or monthly basis by timing how long it took to fill a known volume at the selected site.

To be consistent with other researchers on Banks Peninsula springs, magnitude of discharge has been divided into:

1) low flow (<2.5 l/min)
2) medium flow (2.5 - 15 l/min)
3) high flow (>15 l/min)

Namjou (1988) notes that in general the highest magnitude springs are found at the highest altitudes, due to the higher rainfall that occurs in these areas. The writer has shown that of the 63 high magnitude springs that occur at Diamond Harbour, 59 or 94% discharge from the Herbert Peak Hawaiites and Orton Bradley Formation lavas (Fig. 2.5). These lavas form a cap to the study area, and hence occur at high altitude.

The distribution of high magnitude springs is based on firstly, geological factors, which determine whether certain formations will make good aquifers or not. For example closely jointed lavas will make better aquifers compared to massive unjointed lavas, because the volume of interconnected fracture void space in the former allows for greater storage and transmission of groundwater. Secondly, topographic factors, whereby the rocks that cap ridge tops have a greater surface area and lower relative slope angles, which facilitates the recharge process. Thus, surface runoff is less on some ridge tops than would occur on those with steeper slopes. Thirdly, the higher rainfall that usually occurs on these ridge tops (which is often orographic in origin) is obviously significant in producing high magnitude springs, but not all high rainfall areas found on Banks Peninsula have large numbers of high magnitude springs.

Figure 4.15 from Todd (1980) shows that significantly large springs can issue from rather small catchment areas. Davis and De Wiest (1966) used this figure to illustrate precisely the phenomenon found on Banks Peninsula - the presence of relatively large springs near ridge lines. Actually, the springs are always found below the crests of the peaks and have catchment areas of several tens, if not hundreds, of hectares (Davis and De Wiest, 1966). Geological conditions must be favourable for high magnitude springs to be found under these conditions.

4.5.2 Seasonal Discharge Variability

Table 4.7 is a summary of the discharge variabilities for 12 springs from this study, together with springs from the studies of Sanders (1986) and Namjou (1988). Spring discharge variability over a specified period is defined by Davis and De Wiest (1966) as:

$$Va = [(Qmax - Qmin)/Qmed] \times 100$$

where Va = spring variability
Qmax = maximum discharge
Qmin = minimum discharge
Qmed = median discharge

Spring discharge variability is determined by three principal factors:

1) aquifer permeability
2) area contributing recharge to the aquifer
3) quantity of recharge

Other factors include evapotranspiration rates for vegetation cover and atmospheric pressure changes where confined systems exist.

Figures 4.12 to 4.14 show that spring discharge varies seasonally, with a distinct seasonal maximum occurring for the months June through to October and a seasonal minimum between November and May. Similar trends have been observed

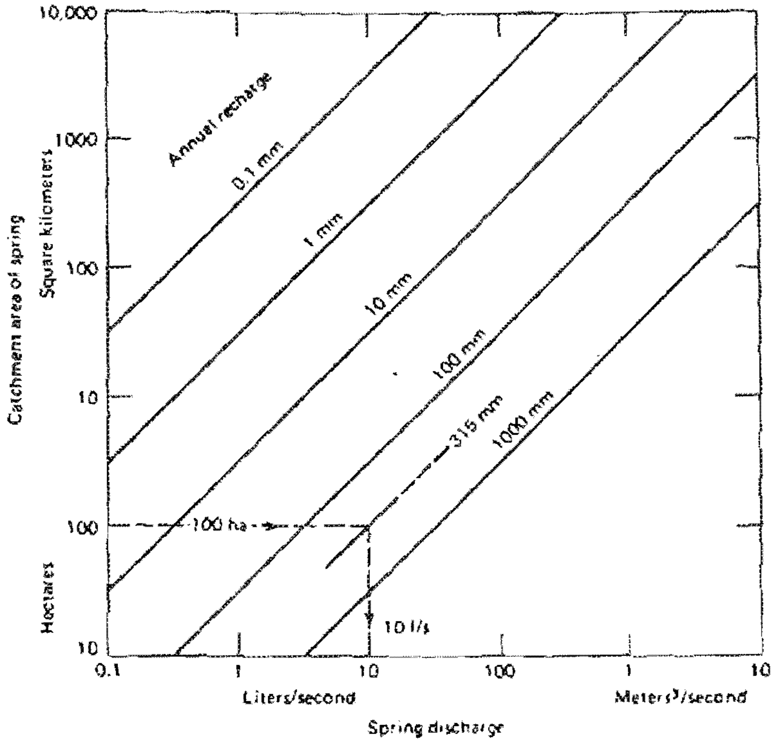


Fig. 4.15 Relation of catchment area and annual recharge to average spring discharge (From Todd, 1980)

Table 4.7 Spring Magnitude Variability

(Refer to text for terminology)

Spring Number	Variability (%)
X1	447
X7	250
X14	255
X15/16	593
4	433
6	804
7	857
9	548
13	660
14	1000
19	808
25	550

for springs in Akaroa County and Kaituna Valley (Sanders, 1986; Namjou, 1988).

Discharge variability appears to be dependent on the amount of recharge occurring and the seasonal evapotranspiration rates. Sanders (1986) notes that maximum recharge usually occurs in the winter months in combination with the lowest evapotranspiration rates, as conditions then favour recharge. During the growing season recharge is generally less and evapotranspiration rates are at their highest, but this will vary depending on the type of local vegetation. This can be seen in Figures 4.12 to 4.14 where a significant amount of rainfall occurred in late January and February 1988. Spring discharge response was minimal, indicating that rainfall was used to replenish soil moisture levels, supply the necessary moisture for plant growth, and account for high evaporation losses.

The summary of water balance calculations given in Table 3.5 for the whole of the Purau Valley shows that, with the exception of two weeks (17/6 - 23/6/88 and 15/7 - 24/7/88) all rainfall over the water balance period produced quickflows of less than one millimetre. This trend continued through the winter months, indicating that most precipitation was used to replenish soil moisture deficits and losses from evapotranspiration. Spring magnitudes had begun to recover by June of 1988 when evapotranspiration losses would be at their lowest.

4.5.3 Event Discharge Variability

a) Springs That Derive Their Flow From Soil Moisture

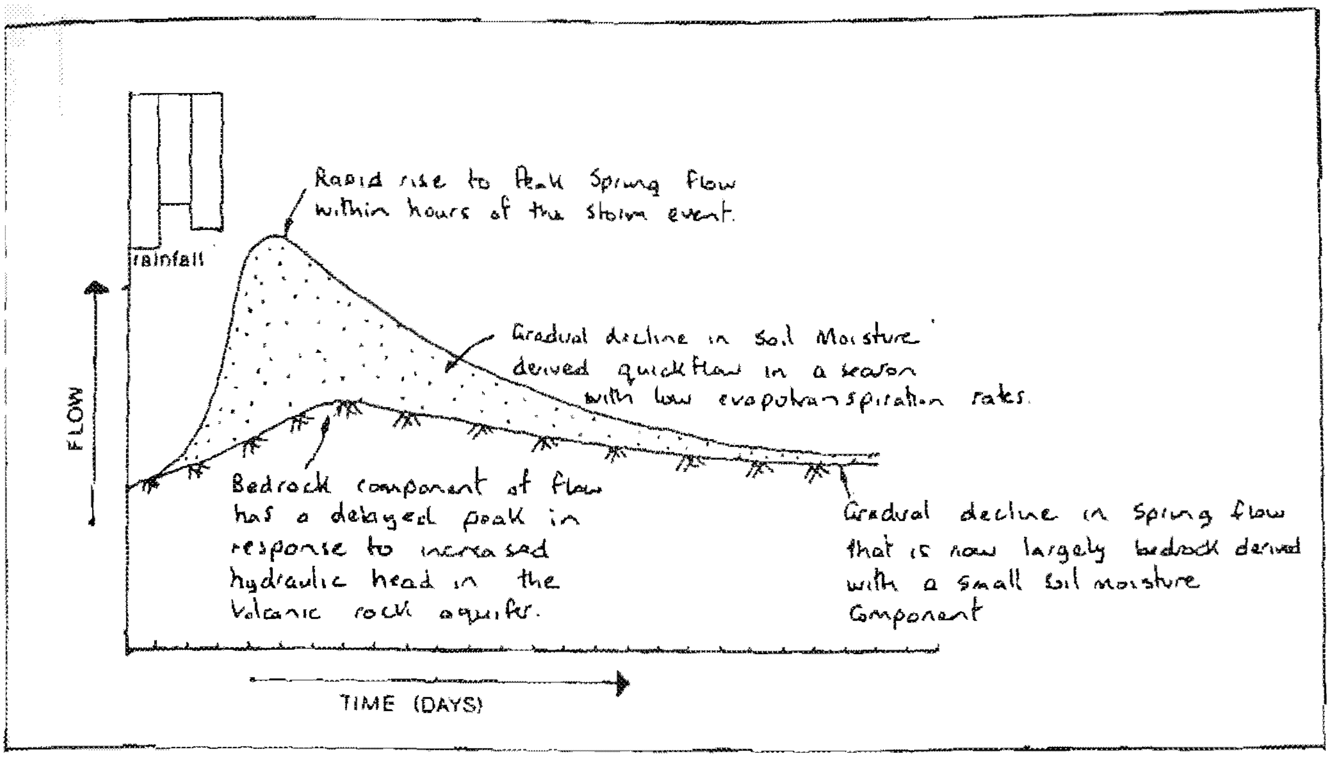
There are very few springs in the study area that derive their entire flow from soil moisture storage. Usually these springs are ephemeral and have low discharge magnitudes and high event discharge variabilities (Fig. 4.2). The entire flow of this type of spring following a rain event is presumably composed of 'new' event water stored over only a few hours to a week or so. As these springs are relatively unimportant further discussion is unnecessary.

b) Springs That Derive Their Flow From Bedrock and Soil Moisture Storage

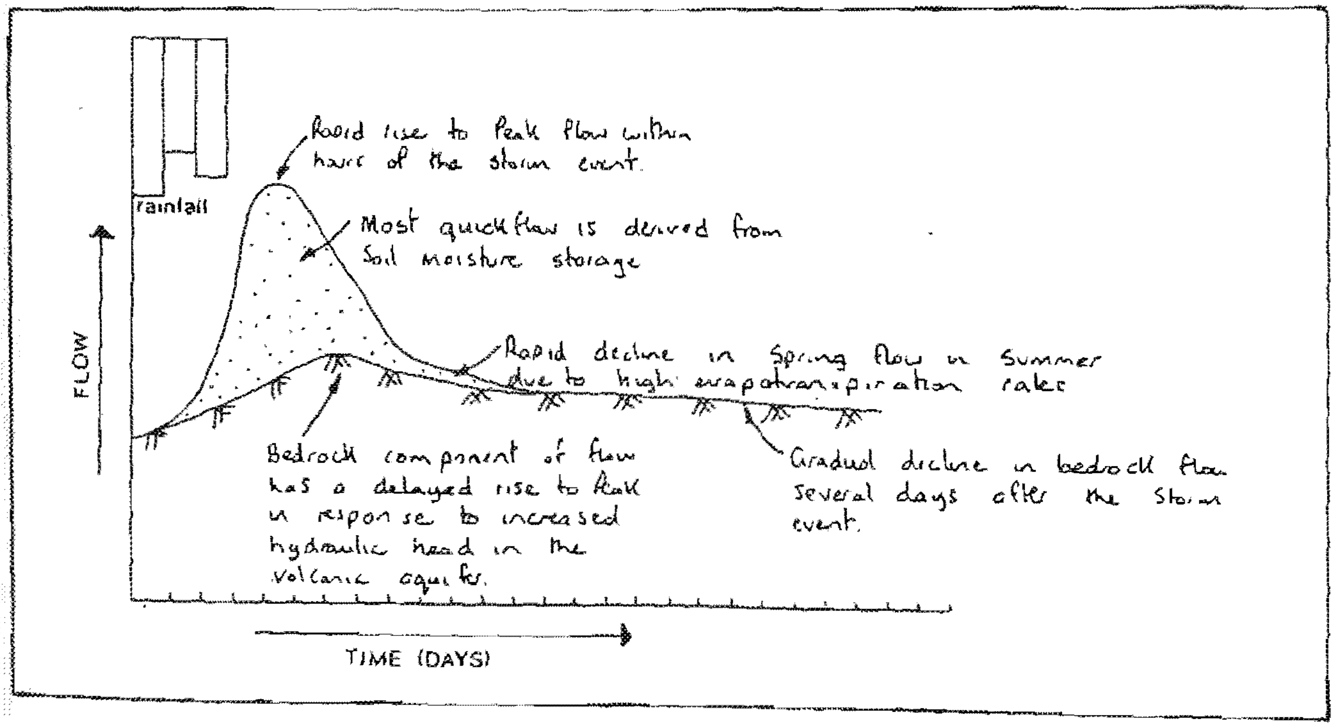
The most common spring type found in the study area are those that derive some component of flow from soil moisture storage which is transfered directly to the point of discharge, and a further flow component of flow from bedrock aquifers (Fig. 4.2). Generally the larger and more important source of water comes from the bedrock aquifers. These springs are usually perennial and can be of low to high discharge. The event discharge variability of these springs tends to be high (ie several hundreds of percent). For example, during the winter when the soil is often saturated, a spring that exits through colluvium will gain a significant component of its discharge from the colluvium and a proportion also from the bedrock aquifer (Fig. 4.16a). This type of spring is observed to show the greatest event discharge variability because of the influence of the soil moisture storage component. During the summer the influence of the soil moisture component is at its lowest due to the generally higher evapotranspiration rates. The flow of this type of spring is presummed to be a mixture of 'old' bedrock stored water (10 to 25 years old) and 'new' event water a matter of hours to weeks in age. The relative amounts of each type of water will depend on the season. During the winter there will be a large component of 'new' water and a smaller relative component of 'old' water whereas during the summer the situation will be reversed (Fig. 4.16b).

c) Springs That Derive Their Flow From Bedrock Storage

The final spring type that has been identified in the study area are those springs that derive their total flow

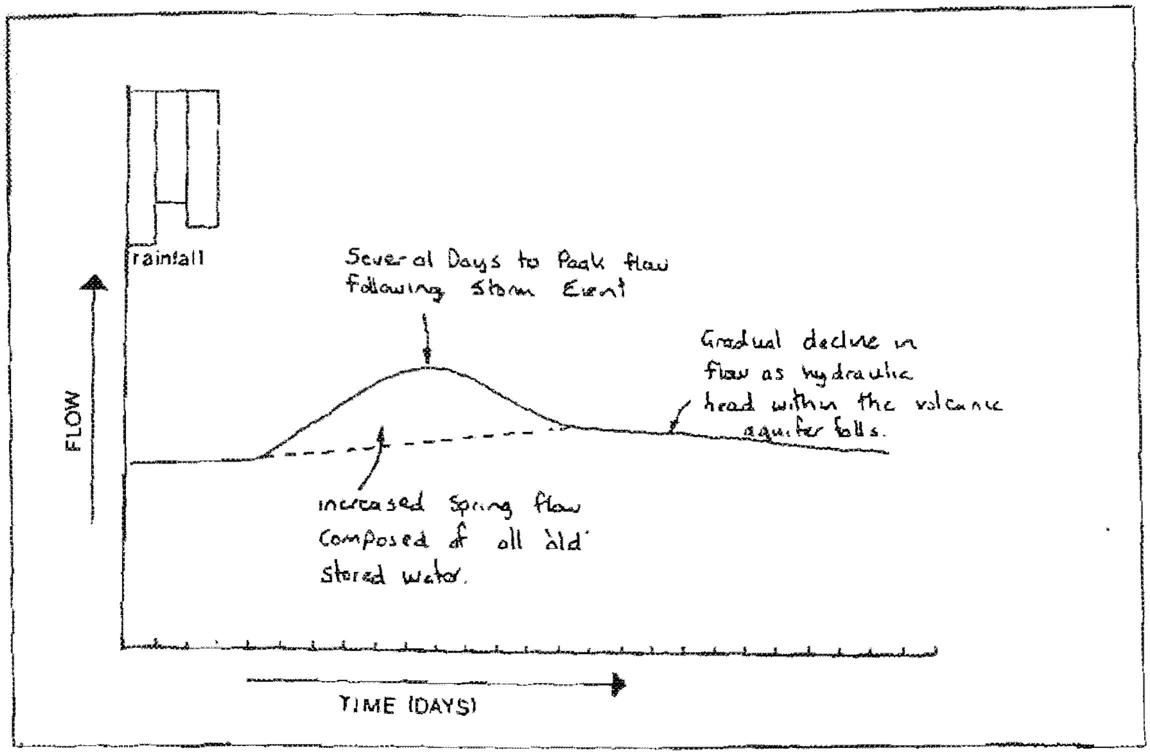


a) Response of a Perennial Spring deriving flow from both bedrock and Soil Moisture Storage to a Winter Storm Event.



b) Response of a Perennial Spring deriving flow from both bedrock and Soil Moisture storage to a Summer Storm event.

Fig. 4.16 Hypothetical responses of a High Altitude Spring that derives flow from bedrock and soil moisture storage to a) a winter storm event and b) a summer storm event.



C) Response of a Perennial Bedrock Spring to a Storm event — winter or summer.

Fig. 4.16 (cont.) Observed response of a High Altitude Spring that derives flow entirely from bedrock storage.

from bedrock storage (Fig. 4.2). The only influence the overlying regolith has on these springs is that the regolith provides the medium by which rainfall is infiltrated to recharge the bedrock aquifers. These springs are not as common as the other types, and are usually found where individual lava flows are exposed as scarps. The event discharge variability of these springs is found to be the lowest (under 200%), as the is no contribution of soil moisture directly to spring flow. Any increase in spring flow following a rain event for this type of spring, is due to an increase in 'head' within the rock aquifers. The entire flow from this type of spring will be derived from 'old' (10 to 25 years residence time) bedrock stored water (Fig. 4.16c).

4.6 SPRING HYDROCHEMISTRY

4.6.1 Background

Two water samples were taken from High Altitude Springs found in the Diamond Harbour area, as follows:

1) Orton Bradley Valley, M36 GR 880263

2) Upper Purau Valley, N36 GR 907239

The origins of the ionic species found in the above samples and the chemical quality of these groundwaters, is discussed in this section. A detailed discussion of the mineralogy of the volcanic formations found in Diamond Harbour is given in Appendix Eight. Chemically, the groundwater of the high altitude springs is similar in terms of ionic species and relative concentrations, to the alluvial and deep groundwater found in the lower valley areas. The most significant difference is that the concentrations of the various ions in the water are generally lower compared to the deep or alluvial groundwater discussed in Chapter Three. The writer believes that the difference between the chemistry of these two types of groundwaters is complex, and results from a combination of several factors that include differing residence times, the chemical composition of local aquifer rocks, and the length of flow path for the groundwater.

Namjou (1988) attempted to relate chemical composition of groundwaters specifically to the length of flow path through the volcanic formations in Kaituna Valley. Freeze and Cherry (1979) quote investigations that have involved tens of thousands of chemical analyses, and they conclude that the chemical composition of groundwater cannot be correlated specifically with distance of travel or residence time, other than to say that in general increased travel distance and time result in an increase in concentrations of total dissolved solids.

4.6.2 Diamond Harbour Spring Samples

Table 4.8 summarizes the high altitude spring chemical results for this study and these results are represented as chemical profiles in Fig. 4.17 . The chemical profiles of the lower valley samples from this study are added for comparison. This study confirms the conclusions of previous studies in that the high altitude spring water from Diamond Harbour tends to be calcium-magnesium-bicarbonate water (Yetton, 1983; Sanders, 1986; and Namjou, 1988).

The following ions tend to dominate the chemical profiles of the High Altitude Spring waters found in Diamond Harbour: Na^+, Ca^{2+}, Mg^{2+} and HCO_3^-. Chloride concentrations tend to be low in these waters. The origins of these ions is assummed to be the dissolution of minerals within the volcanic rock by mildly acidic groundwaters. A discussion of these processes has already been given in Chapter Three.

Table 4.8 Chemical Analyses of Two High Altitude Springs, Diamond Harbour

Sample No.:	R2548	R2445/3
	M36 GR880263	N36 GR907239
ANALYSIS		
Units g/m^3, except pH or unless otherwise stated.		
pH	7.6	6.0##
pH after aeration	8.1	7.3
Acidity to pH 8.3 (as CO_2)	4	14
Total Alkalinity to pH4.5 as HCO_3	67	18
Alkalinity to pH 8.3 (as CO_3)	NIL	NIL
Turbidity (NTU)	1.4*	1.3*
Colour (from Absorbance 270nm) TCU	2	LT1
Absorbance units (270nm, 1cm cell)	0.016	0.003
Chemical Oxygen Demand (as O)	5	LT4
Ammoniacal Nitrogen	LT0.04	LT0.04
Nitrite Nitrogen	LT0.005	Lt0.005
Nitrate Nitrogen	0.13	0.06
Soluble Phosphate (as P)	LT0.06	LT0.06
Sulphate	1.7	1.3
Bromide	LT0.05	0.06
Chloride	14	11
Fluoride	LT0.1	LT0.1
Calcium	12	5.2
Magnesium	5.7	1.6
Potassium	1.0	0.68
Sodium	11	6.8
Reactive Silica (as SiO_2)	26	17
Reactive Aluminium	0.07*	LT0.04
Arsenic	LT0.01	LT0.01
Antimony	LT0.01	LT0.01
Boron	LT0.2	LT0.2
Cadmium	LT0.005	LT0.005
Chromium	LT0.02	LT0.02
Copper	LT0.02	LT0.02
Iron	0.11*	LT0.05
Lead	LT0.05	LT0.05
Lithium	LT0.01	LT0.01
Manganese	LT0.01	LT0.01
Nickel	LT0.05	LT0.05
Selenium	LT0.005	LT0.005
Strontium	0.05	0.06
Zinc	LT0.02	LT0.02
Total Hardness (as $CaCO_3$)	54	19
Conductivity at 20 deg C (mS/m)	15	6.6
Langelier Index at 20 deg C	-1.1	-3.6

The letters LT in the above table mean "less than".
This sample does not comply with the following NZ Standard Guidelines:

outside maximum range
* exceeds lower guideline limit

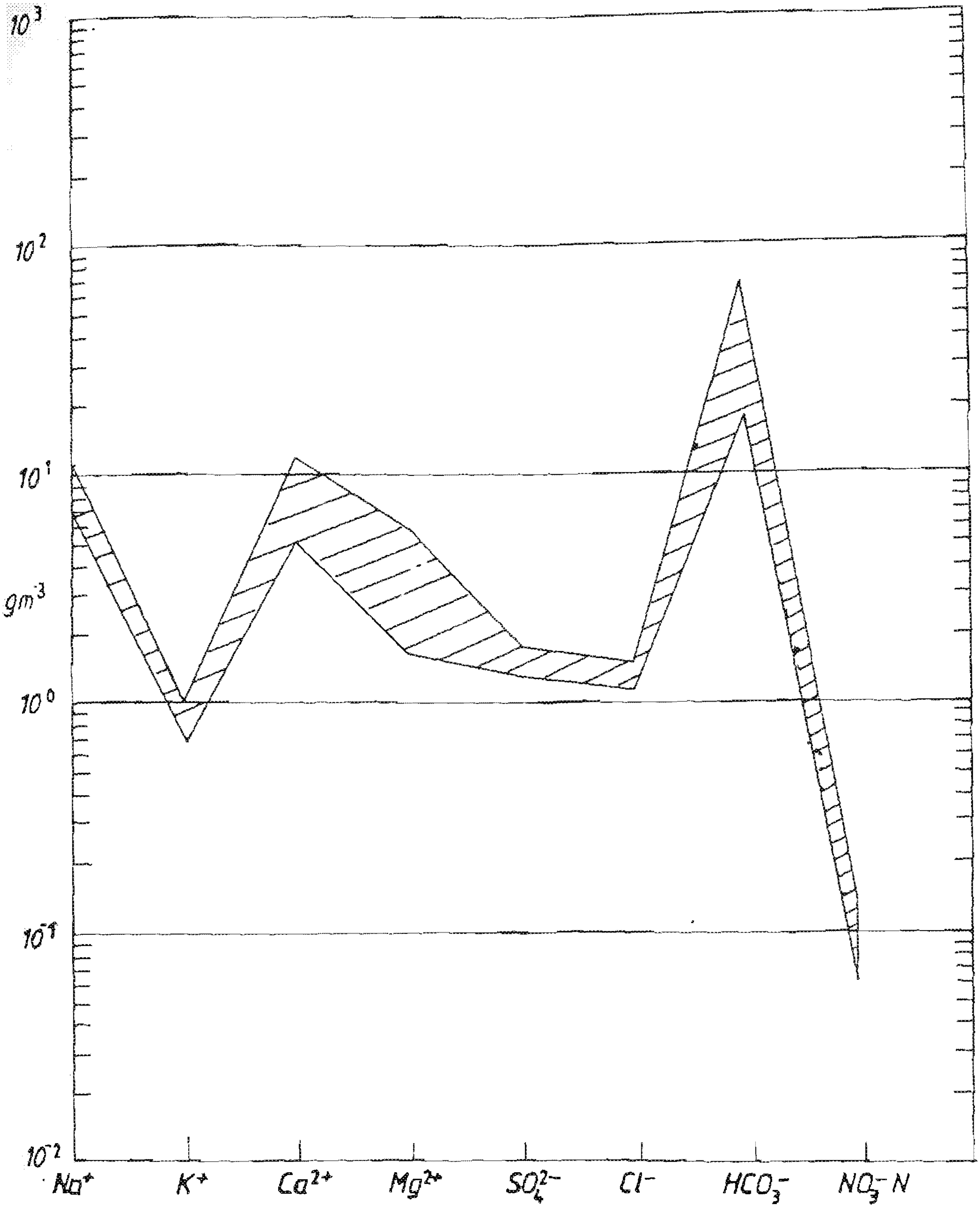


Fig. 4.17 Chemical Profiles of Two High Altitude Springs, Diamond Harbour.

4.6.3 Spring Water Quality

A brief discussion on the quality of the spring waters found in Diamond Harbour is presented in this section. Yetton (1983), Sanders (1986) and Namjou (1988) have presented similar discussions in detail on the spring waters of their respective study areas. Most of their observations regarding water quality are also applicable to this study, and only a brief discussion is presented in this section.

Water quality parameters for domestic drinking water are taken from New Zealand Board of Health, Drinking Water Standards for New Zealand (1984). Any parameter that exceeds the lower guideline limit is marked with an asterisk in Table 4.8, and those that exceed the upper guideline limit are marked with a double asterisk.

1) The two samples tested would be suitable as drinking water with some treatment when concentrations of ionic species such as iron exceed the recommended limits. Where limits are exceeded they are discussed below.

2) The generally low pH of the upper Purau spring water is consistent with a high CO_2 level in the waters and this is a feature of many Banks Peninsula high altitude springs (Dr E.T.J. Bathurst, DSIR, pers. comm.). A consequence of this is that metal water supply fittings will have a life span of only a few years. Aeration will bring the pH of this water within acceptable limits. The pH of the Orton Bradley spring water does not seem to be lowered by the unusually high CO_2 level.

3) Both waters are outside the range for Turbidity levels, the highest desirable limit being one (NTU). This would need to be reduced by coagulation, flocculation or filtration methods but does not pose any real problem.

4) Nitrate nitrogen levels are well below the maximum desirable $10g/m^3$. Fertilizers are not normally used where many of these springs derive their recharge, and stocking rates are not high enough to be an influence on nitrate nitrogren levels.

5) The concentration of iron is at acceptable levels in the Purau sample, but exceeds the lower guideline limit of 0.1 g/m^3 for the Orton Bradley sample. In Chapter Three it was shown that the origin of the iron is the ferromagnesiam minerals common in the reservior rocks. High iron concentrations will lead to discolouration of the water, tainting, deposit formation and staining of laundry and plumbing fixtures. Aeration is a cheap method of reducing iron concentrations and pH levels to acceptable levels.

6) The Orton Bradley sample has an aluminium concentration greater than the highest desirable limit. This could lead to water discolouration and deposit formation on metal water supply fittings.

7) The upper Purau Valley sample is classified as soft water, whilst the Orton Bradley sample is moderately soft water (Table 2.2). No problems of scale formation in hot water cylinders or electric element burn out should be experienced with these waters.

8) These two spring waters are found to be typically representative of the chemical state found for most high altitude springs on Banks Peninsula (Fig. 2.18).

4.7 A REVISED HIGH ALTITUDE SPRING MODEL

Observation of high altitude springs in the Diamond Harbour area and elsewhere on Banks Peninsula suggests that associated groundwater is stored in irregularly shaped perched water bodies in the closely developed columnar jointed lavas found in the area (in this case Herbert Peak

Hawaiites and Orton Bradley Formation lavas). An exponential-piston flow model is proposed, as water in these hard rock aquifers is well mixed and the mean residence time of spring water is in the range 10 to 25 years. Water not lost to springs is held in storage or lost to deeper groundwater. Residence times for other springs on Banks Peninsula may differ from those found in Diamond Harbour for example, Namjou deduced from tritium measurements taken from some Kaituna Valley High Altitude Springs that spring waters had residence times of less than five years.

Recharge is entirely of meteoric origin for these springs, and enters the predominantly unconfined aquifers by direct infiltration through sub-vertical fractures and by slow 'leakage' over a period of up to about four days, through the regolith.

Calculations indicate a total volume of approximately 50 x $10^6 m^3$ of rock above the 760m contour (Fig. 4.7), and based on residence times of 10 - 25 years (and assuming a mean flow of $295m^3$/day for springs X1 - X18), then the total reservior size for the Upper Purau Valley lies in the range 1 x $10^6 m^3$ to 2.6 x $10^6 m^3$. These volumes represent between 2% and 5% of the total rock volume. Calculations also reveal that spring X1a has a reservior size of between $39{,}000m^3$ and $97{,}000m^3$, representing approximately 4% of the total reservior size of between 1 x $10^6 m^3$ and 2.6 x $10^6 m^3$. It would be possible with similar information to make estimates of reservior sizes for most areas in Banks Peninsula where springs occur.

Flow and isotopic data indicate that there is both seasonal and 'storm event' variability of spring flow. Spring discharge varies according to the amount of recharge being received. This will normally reflect seasonal trends, the greater recharge being received during the winter months where a combination of low evapotranspiration rates and higher rainfall conditions exist. The winter season of the study period was atypical, in that it was the driest winter experienced for several decades but despite this, significant recharge of around 3 to 7% of the total reservoir volume was still achieved.

The evidence suggests that the prevailing soil moisture situation has a direct influence on recharge to the volcanic aquifers. The existance of a soil moisture deficit or surplus in the regolith will dictate whether a rainfall event will cause an increase in spring discharge. Order-of-magnitude calculations suggest that most recharge is derived through the soil column, with a minor component through direct infiltration via sub-vertical fractures in the volcanic rock. It appears that a high soil moisture surplus (around 75mm) must exist before there is any noticeable increase in spring flow. Until this surplus is reached, there will be little effect on bedrock-derived spring flow.

When the necessary soil moisture surplus has been reached, bedrock spring response time to a rain event is usually rapid. Springs will respond within 24 hours of an event, or if the event fell as snow then usually within 72 hours depending on radiation levels. However, it may take several days to reach peak flows from bedrock springs. Peak flows will be reached very rapidly (usually within 24 hours) if the spring derives part or all of its flow from soil moisture storage. This evidence suggests that an infiltration "head"/storage model will explain the behaviour of Diamond Harbour High Altitude Springs. Recharge to the springs results in an increase in hydraulic head within the system, and this produces an increase in output as increased spring flow.

4.8 SYNTHESIS

Field studies reveal that the majority of High Altitude Springs in the Diamond Harbour area are located within the Herbert Peak Hawaiites and the lavas of the Orton Bradley Formation. The lavas of these volcanic formations possess well developed columnar joints and basal breccias which cap the ridge tops and allow the transmission and storage of groundwater. Observations show that the surficial cover in the field area acts as a medium for the temporary storage of groundwater before it is slowly leaked to recharge volcanic rock aquifers.

A field experiment on a perennial bedrock spring located in the upper Purau Valley revealed that a "head"/storage model in combination with a precipitation-infiltration model is appropriate for the springs of the Diamond Harbour area. Tritium measurements indicate that an exponential-piston flow model approximates the age distribution of spring X1a groundwaters, and gives a mean age for this spring water between 10 and 25 years. Daily oxygen-18 measurements indicate that the increased flow of spring X1a in response to a storm event was all 'old' well mixed water. There appeared to be no component of 'new' storm water in the spring hydrograph.

An approximate reservior volume of between 1×10^6 and $2.6 \times 10^6 m^3$ was calculated for the upper Purau Valley, and this represents between 2 and 5% of the total volume under consideration. Water balance calculations for the period 18/8/88 to 8/9/88 indicate that recharge of between 3 and 7% of the reservoir occurred over this time.

Studies showed that springs that derived flow entirely from a bedrock origin would have a lower flow magnitude variability compared to springs that derive flow from bedrock and soil moisture storage. Chemical analyses of the two high altitude springs indicates these water derived their ion concentrations from the dissolution of minerals within the volcanic rock. The concentrations of ionic species within these groundwaters were generally well below the acceptable maximums, and only minimal treatment is necessary to meet NZ DWS.

CHAPTER FIVE

MANAGEMENT IMPLICATIONS

5.1 BACKGROUND

To supply all the domestic water needed for the Diamond Harbour township, a flow of approximately 100 m^3/minute is required. This volume of water also allows for the projected population growth expected when vacant residential land is developed in the next few years. Four water resource options are available for the development of a domestic water 'town supply' resource in the Diamond Harbour area:

1) Purau and Orton Bradley river waters.
2) Valley floor alluvial groundwater.
3) High Altitude Springs.
4) Deep groundwater stored in bedrock aquifers.

The Purau and Orton Bradley Rivers normally flow all year round, however at least once within living memory the Purau River has run dry during an unusually dry summer. Chapter Three discussion suggests that any alluvial groundwater found in the Orton Bradley Valley will only be sufficient to supply the needs of individual households, whereas the Lower Purau Aquifer is already producing locally significant quantities of groundwater for domestic use.

A large number of High Altitude Springs are to be found in both the upper Purau and Orton Bradley Valleys, and development of this resource for the Diamond Harbour township may be a possibility. The investigation also indicates that located within fractured and jointed volcanic rocks of the Purau and Orton Bradley Valleys is a resource of deep circulating groundwater that could be useful for domestic water supply. In this Chapter possible management options that relate to each of these water resources are examined, as well as current groundwater and surface water use in the area.

5.2 CURRENT WATER USE

5.2.1 Surface Water Usage

a) Orton Bradley Valley

Surface water resources are already being utilized to a degree by some local residents of the Orton Bradley Valley. It is difficult to quantify the current water use as irrigation is only used on an irregular basis, however when irrigation is being used extraction would probably run into several tens of cubic metres/day. The low density of dwellings in the Orton Bradley Valley means that only a few residents have made use of this resource to date, for example surface waters are occasionally used by the Charteris Bay Golf Club to irrigate greens in the lower valley areas.

b) Purau Valley

Several residents of the Purau Valley regularly utilize river water for irrigation and domestic supply during the summer months. Individual households are also known to pump water directly from the Purau River to supplement rain water for drinking purposes, and to water gardens. Pumping from the Sulphur Spring creek also occurs on a regular basis to irrigate tomato crops and pastures during the summer. The Purau Motor Camp has a water right to remove a total of up to $100m^3$/day for domestic use over the summer period. This figure includes provision for up to $30m^3$/day to be pumped from well 13 which penetrates the Lower Purau Aquifer.

5.2.2 Valley Floor Alluvial Groundwater

Two houses in Charteris Bay (Orton Bradley Valley) located within 50m of the coast have shallow (<3m) dug wells from which fresh goundwater can be extracted to water gardens, however these houses still relie on rain water for drinking purposes. No other wells located within the alluvial sediments of the Orton Bradley Valley are known to the writer.

Nine shallow (<5m deep) driven wells penetrate the Upper Purau Aquifer, and these supply water for the toilet systems and gardens of six Purau Valley households. Occasionally the water from this aquifer is used as drinking water, but most residents reserve rain water specifically for this purpose.

A further four deeper wells (6 to 12.9m deep) penetrate the Lower Purau Aquifer, and this water is used for all domestic purposes. Two of these wells are located within the Purau Motor Camp, and the remaining two are located on properties owned by L. Gay and T. Long. The new Purau Motor Camp well (well 14) has been drilled and screened while all the others are driven pipes with slotted bases. Well 11 (Fig. 2.3) did not penetrate the targeted Lower Purau Aquifer and has been capped and abandoned.

In cases of wells that penetrate the Lower Purau Aquifer, water is pumped either continuously or intermittently into storage tanks. The Purau Motor Camp has a 5000 gallon (approximately 19000 litres) storage tank that has an automatic controlling device. When the water level drops in the tank below a given level, the well pump is started and pumping continues at 7 gallons/minute (26 litres/minute) until the storage tank is filled. Treatment involves spraying the water over a gravel bed to aerate it and to oxidise the iron which is then removed as a precipitate. As pumping is intimitant it is not possible to say what quantities of water are actually currently extracted on a daily basis. The water right to extract $100m^3$/day can consist of both river and well water, with the limitation that only up to 30m3/day can be removed from the well.

5.2.3 High Altitude Springs

Where possible farmers and residents of both the Purau and Orton Bradley Valleys have tapped into spring water sources to provide domestic and stock drinking sources. Domestic water supplies for the Orton Bradley Park Farm are derived from a spring-fed perennial stream at M36 GR 876262 (Figs. 2.2 and 2.5). This intake is located at an altitude of 230m a.s.l. on the western flank of the Diamond Harbour dip-slope, and the water is gravity fed to the farm house in the valley below. Three households of Purau Valley derive domestic supplies from a dammed collection point at M36 GR 900280, and this water is derived from a high magnitude perennial spring at M36 GR 892271 on the eastern flank of the Diamond Harbour dip-slope (Figs. 2.2 and 2.5).

The method for supply in both cases consists of channelling spring water to a collection point where the water is stored, and polythene piping is then used to pipe the water to individual households (Fig. 5.1). Several disadvantages exist with this system. Where water is dammed and fed off to households (as in the Purau Valley example) the dam is not effectively closed off to stock and hence the water is liable to contamination. Even if the dam is closed off to stock, contamination is still possible further upstream.

Local farmers have utilized a similar system for their own domestic and stock supplies. High magnitude perennial springs near Mt Herbert have been dug out and collection points established at the spring source. Water is then fed by polythene piping into small concrete tanks. Water is in

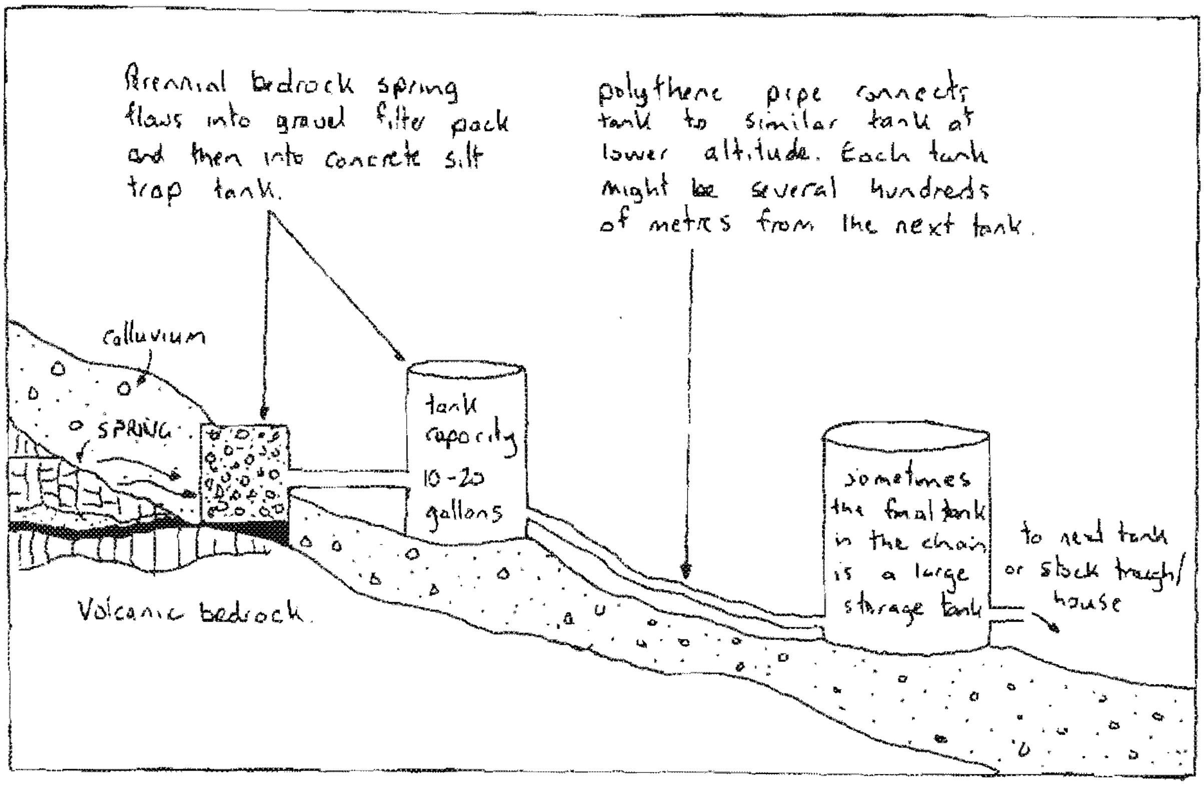


Fig. 5.1 A method of transferring High Altitude Spring waters to points of use at lower altitudes on the Diamond Harbour dip-slope. The topography must be favourable for this system to work.

turn fed from these tanks to tanks at lower altitude until the points of distribution are reached (Fig. 5.1). Clearly if this system is to work the topography must be favourable, and this factor limits the number of springs that can be developed in this manner.

5.2.4 Deep Circulating Groundwater

Two sources of what is considered deep circulating groundwater have been identified, the Sulphur Spring (Purau Valley) and the artesian water issuing from the 220m deep well in the Orton Bradley Valley. At the present time each of these sources contributes their entire flow to the Purau and Orton Bradley Rivers above the main extraction points for each of these rivers. As previously mentioned, occasionally water is pumped directly from the Sulphur Spring for irrigation purposes.

5.3 SAFE YIELDS

5.3.1 Assumptions and Methodology

In the following discussion an attempt to quantify the water resources available in the Diamond Harbour area is made so that effective management strategies can be developed. Peak water demands occur during the driest months of the year when High Altitude Spring and surface waters are at their lowest flows, and calculations are therefore based on average low flows that occur at this time of the year.

The flow record available for the Purau River extends over the period 19/1/88 to 4/8/88. The average low flow of about 20 litres/second over the summer of 1988 for the Purau river was taken from the calculated hydrograph given in Figure 3.18. This flow was used to calculate daily minimum river flows available for use. As no hydrograph was available for the Orton Bradley river, the figure of 17 litres/minute was taken from stream gaugings recorded over the summer of 1988, and this represented the lowest flow calculated during this period.

Calculations of the anticipated safe yield of the Purau Motor Camp well (well 13) are based on data from the pump test carried out on well 13 during August 1988. The total safe yields available from the Lower Purau Aquifer will clearly be several times the safe yield of well 13, but accurate estimation of this figure will require further well monitoring, and possibly the siting of further observation piezometers.

Estimation of the safe yields from the known sources of deep circulating groundwater are based on measured minimum flows. The flow from the Orton Bradley deep well used in the following calculations was a single measurement taken in April 1988. Further monitoring of the flow of this artesian well will be required to determine if flows vary seasonally.

5.3.2 Surface Waters

Based on an average low flow of 20 litres/second for the Purau River over the summer season of 1988, the total yield of this river is approximately 1728m^3/day. If the removal of up to one third of this flow is considered a safe yield, then up to 576m^3/day can be drawn from the Purau River for all purposes. The above figures were taken during the 1988 summer season which followed an 'average' winter season (ie the 1987 winter where recorded rainfall represented an average season), where it can be assumed that the volcanic springs that provide most river base flow during the summer were fully recharged.

Based on an average low flow of 17 litres/second for the Orton Bradley River over the summer season of 1988, the total yield of this river is approximately 1500m^3/day. Again, assuming removal of up to one third of the flow consitutes a safe yield, then up to 500m^3/day can be safely removed for all purposes.

If an unusually dry winter occurs (as for example in 1988) then it is likely that the summer baseflows for both the Purau and Orton Bradley Rivers will be significantly reduced over the summer of 1988/89, and hence lower safe yields must be expected.

5.3.3 Valley Floor Alluvial Groundwater

Based on pumping test data, a well such as well 13 or 14 located in the Purau Motor Camp will produce about 20m^3/day. This figure is based on a pumping rate of 30 litres/minute for about 10 hours/day. Due to the system used at the Motor Camp, the length of sustained pumping time varies depending on the usage from the storage tank, but usually does not continue beyond 40 to 60 minutes. This allows recovery to occur between pumping sessions, and it may be that more than 20m^3/day can be safely extracted from this well.

If other wells are put down and extract water from the Lower Purau Aquifer, monitoring of piezometric levels will need to be carried out on a regular basis to determine the effect of the increased extraction rates. It would be unwise to allow the hydraulic gradient in this aquifer to drop below zero as sea water intrusion may occur. An estimated total safe yield from the Lower Purau Aquifer could be between 60 and 100m^3/day.

Yields from the Upper Purau Aquifer can be expected to be low as it was found that the saturated portion of this gravel unit was limited to within about 200m of the coast. An estimated total safe yield from the Upper Purau Aquifer could be between 20 and 40m^3/day.

It is expected that the safe yield from the Orton Bradley Aquifer would be low and only sufficient for a few households, but could be estimated at between 20 and $40m^3$/day.

5.3.4 High Altitude Springs

Spring flows for the upper Purau (springs 6-12, X1-X18) and Orton Bradley (springs 13-25) Valleys (Fig. 2.5) indicate that on the 18/1/88 during the dry summer period total spring flows were about $200m^3$/day and $50m^3$/day, respectively (Appendix 11). These figures do not represent the total daily flow derived from all the High Altitude Springs of each of these catchments, as not all of the springs were gauged on a regular basis, and some high magnitude springs were only located towards the end of the study. Despite this limitation, an estimate of total daily High Altitude Spring flow from the Purau and Orton Bradley Valleys could be between 200 and $600m^3$/day and 50 to $300m^3$/day respectively.

5.3.5 Deep Groundwater

During the summer of 1988 the baseflow of the Sulphur Spring was about 40 litres/minute ($57m^3$/day), while the flow of the Orton Bradley deep well was about 50 litres/minute ($72m^3$/day). It is possible that exploratory drilling would intersect other fractured bedrock aquifer systems in the area and therefore this resource could provide locally significant quantities of groundwater. As these deep groundwater systems are to be found in the lower valley areas their usefulness will be limited by the necessity to have some type of pumping system to pump the water up-slope to the Diamond Harbour township. Removal of deep groundwater for domestic use may also have an effect on the flow of the springs thought to exit on the Lyttelton Harbour sea floor.

5.4 DEVELOPMENT OPTIONS

Several options are available for the development of a water resource for the Diamond Harbour township. This section presents a brief discussion of some of these options, and a summary of the inter-relationships between the different water resources found in the Diamond Harbour area.

5.4.1 Surface River Waters

Table 5.1 is a summary of the estimated total water resources available in the area based on average summer flows which occur during the period of peak demand. Clearly the largest resource available is the surface waters of the Purau and Orton Bradley Rivers. Development of these surface waters could be carried out by direct pumping from the rivers to storage tanks located in Diamond Harbour. Extraction points along each river could be sited far enough up-valley so that minimal pumping was required. Alternatively, some type of dam could be located on either the Purau or Orton Bradley Rivers. This alternative has been examined in the past by Lyttelton Borough Council Engineers and plans were drawn up for a dam to be located at approximately N36 GR 901288 to store water for Diamond Harbour. Both the Purau and the Orton Bradley Valleys appear to have suitable sites for water storage reservoirs, however further investigations would be required to determine the feasibility of this option.

5.4.2 Alluvial Groundwater

A second option involves development of the alluvial groundwater resource. Table 5.1 indicates that a total of only 60 to 140m^3/day would be available from the Purau Valley Aquifers and this could be used to supplement other water sources that supply Diamond Harbour. This would involve pumping the groundwater to holding tanks in Diamond Harbour before distribution to individual households.

5.4.3 High Altitude Springs

Tapping the High Altitude Spring resource in both the Purau and Orton Bradley Valleys could provide between 250 and 900m^3/day over the summer months. However, it has already been stated that the baseflow of both the Purau and Orton Bradley Rivers is largely maintained by the flow from these High Altitude Springs, and removal of spring flow will reduce river baseflows by a corresponding amount (Fig. 5.2). If this option were to be considered, either individual springs or sections of the spring fed tributaries of the Purau and Orton Bradley Rivers would need to be selected as intake points. If individual springs were selected, these would need to be closed off to stock and developed. Development might consist of physically enlarging the spring exit by excavation or by tunnelling into the bedrock to allow easy collection of the water and possibly to increase flows. A danger of attempting to increase flows by excavation would be that springs might cease to flow due to aquifer depletion. A second disadvantage of developing large numbers of individual spring sites, is that it would be a labour intensive operation at the outset and would require continual maintenance to keep springs freely flowing.

It would be possible to locate small dams in the upper reaches of each valley to provide collection points for spring waters, and from these small reservoirs water is gravity fed to holding tanks in Diamond Harbour. An advantage of this option is that the number of collection points is reduced to a minimum and so maintenance problems would be kept to reasonable levels. A second advantage of this option is that sufficient spring water could be allowed to over flow dam sites to maintain river baseflows. This will require careful monitoring of spring flows so that the extraction rates do not reduce river baseflows to unacceptable levels, however this system would be flexible

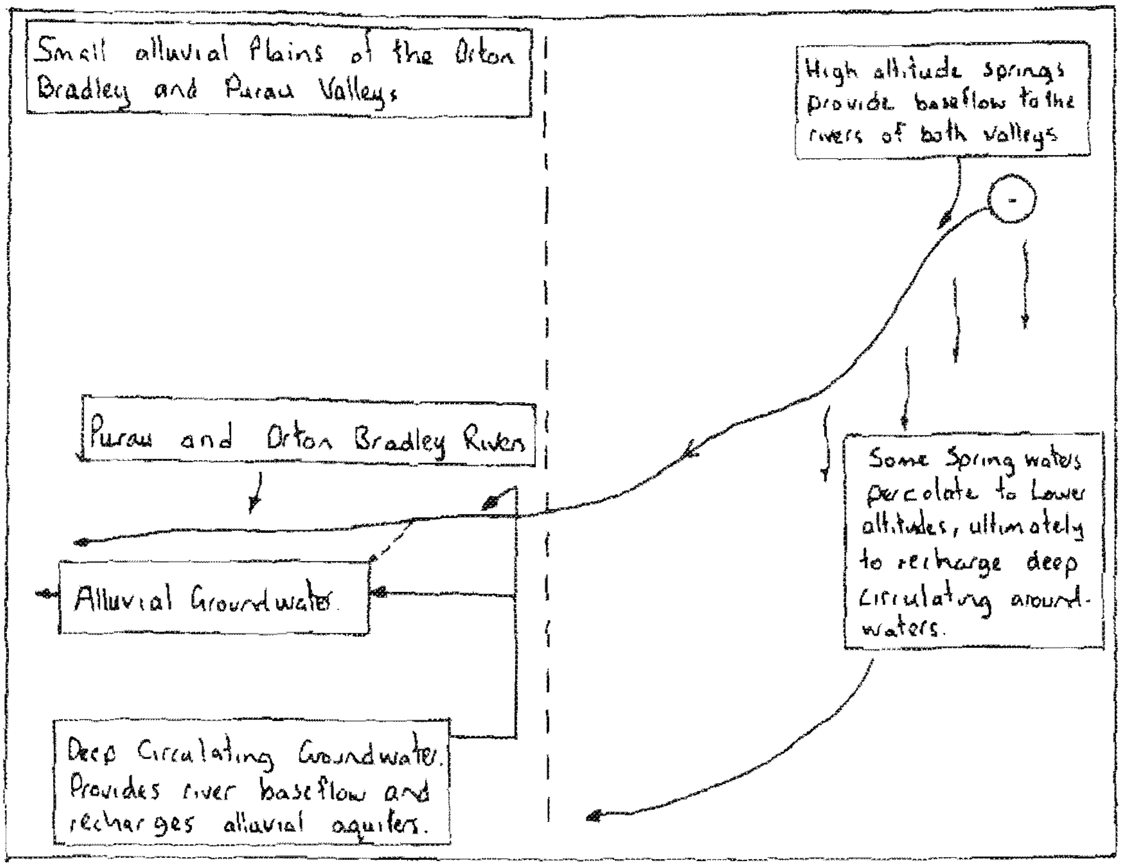


Fig. 5.2 Diagram showing the interrelationships between the different water resources found in Diamond Harbour. The dashed line represents a possible hydraulic connection between the Purau River and the Upper Purau Aquifer. Clearly, any removal of spring water will reduce the base flow to either river.

Table 5.1 Total available flows by resources. Flows based on minimum summer (1988) records.

Resource	m^3/day
Purau River	576
Orton Bradley River	500
Upper Purau Aquifer	20 - 40
Lower Purau Aquifer	60 - 100
Purau High Altitude Springs	200 - 600
Orton Bradley High Altitude Springs	50 - 300
Deep Groundwater	
a) Purau Sulphur Spring	57
b) Orton Bradley Deep Well	72

enough to allow variable extraction rates to overcome this problem.

5.4.4 Deep Groundwater

Development of the resource of deep groundwater would require essentially the same methods that would be used to develop the river water resource. A limitation associated with the deep groundwater is that the two sources currently known provide a significant contribution to summer river baseflows (Fig. 5.2). It might be possible to increase the flow of the Sulphur Spring (Purau Valley) by drilling a well adjacant to the spring itself. Other sources of deep groundwater might be located by further exploratory drilling in the lower valley areas, however all deep groundwaters would require pumping to holding tanks located in Diamond Harbour.

5.4.5 Summary of Available Water Resources

It is difficult to accurately quantify what the total available water resource in the Diamond Harbour area would be without affecting river baseflows, however it seems likely that during an average summer period it would amount to between 600 and 1200m^3/day from river, High Altitude Spring and deep groundwater resources, with perhaps a small contribution of around 60 to 100m3/day from the alluvial groundwater resource. Clearly, if some type of storage system were available to hold some of the winter flows from any of the resources discussed, then the total available water resource would be significantly increased.

5.5 FURTHER INVESTIGATIONS

Current investigations indicate that a total of about 660 to 1300m^3/day can be safely utilized from all the available water resources during the summer months. These figures compare with the total estimated future requirement of around 144,000m^3/day for the Diamond Harbour township.

Clearly, the local water resources can only be expected to provide a small contribution to the daily needs of the township or to act as an emergency supply when necessary.

If river water or High Altitude Spring water is to be utilized then the investigation shows that minimal water treatment is required, consisting mainly of aeration to bring the low pH of these waters to within acceptable limits and possible filtering to reduce the levels of suspended matter. If the alluvial and deep groundwaters are to be utilized, then treatment for high iron and manganese concentrations, hardness levels that exceed desired limits and treatment for low pH levels will be necessary.

The following lines for future investigation are recommended to allow for effective development and management of the water resources found in the Diamond Harbour area.

1) Further exploratory drilling in the sediments of the Purau Valley and an exploration hole in the Orton Bradley Valley sediments.

2) A possible deep exploration borehole in the Purau Valley to locate the fractured bedrock aquifer that is considered to recharge the alluvial aquifers of the Purau Valley.

3) A continuous monitoring of one or more wells in the Purau Valley (both in the Upper and Lower Aquifers) over an annual period to accurately determine piezometric level fluctuations within these aquifers and their response to tidal changes.

4) Continuous flow monitoring of the Sulphur Spring to determine flow patterns over an annual period. Annual or once every two yearly tritium sampling of this spring is also recommended.

5) Spring experiments similar to those discussed in Chapter Four, should be set up for an annual period on a further one or more accessible High Altitude Springs to confirm the applicability of the conclusions reached in this investigation, to other High Altitude Spring on Banks Peninsula.

6) The surveying of known perennial High Altitude Springs and possible small dam sites located in the upper Purau and Orton Bradley Valleys to determine which sites are suitable for development.

5.6 SYNTHESIS

Four water resource options have been examined to assess their potential for the development of a 'town supply' resource for Diamond Harbour. These include surface river waters; valley-floor alluvial groundwater; High Altitude Spring waters, and deep circulating groundwater.

Current water usage consists of occasional direct pumping from both the Purau and Orton Bradley Rivers for irrigation and sometimes for domestic drinking water during the summer months. Pumping from both Purau aquifers by several residents provides water for gardens and drinking purposes where the largest user of alluvial groundwater is the Purau Motor Camp. Farmers and some local residents have developed the occasional perennial High Altitude Spring to supply domestic and stock drinking water. Finally, direct pumping from the Sulphur Spring (considered to be deep circulating groundwater) in the Purau Valley occurs on a regular basis for irrigation.

Estimates of the available water resource from each of the four sources discussed is based on average summer flows calculated over the study period, and includes:

- about $576m^3$/day and $500m^3$/day from the Purau and Orton Bradley rivers,

- about 80 to 140m^3/day from both the Purau alluvial aquifers,
- about 200 to 600m^3/day and 50 to 300m^3/day from the High Altitude Springs of the Purau and Orton Bradley Valleys, and
- about 53m^3/day and 72m^3/day from the Sulphur Spring and Orton Bradley deep well.

As almost the entire baseflow for the rivers is provided by High Altitude Springs and deep circulating groundwater, a total safe yield from all four resources in both the Purau and Orton Bradley Valleys, is calculated at about 660 to 1300m^3/day. Removal of this amount of water from all resources should keep river baseflows at acceptable levels.

Development options include: dams on the lower reaches of either the Purau or Orton Bradley Rivers; pumping of alluvial and deep circulating groundwater from both valleys to storage tanks in Diamond Harbour; a series of small dams located on the spring fed tributary streams in the upper reaches of each valley, from which water is either gravity fed or pumped to storage tanks in Diamond Harbour, or development of individual perennial High Altitude Springs.

CHAPTER SIX

SUMMARY AND CONCLUSIONS

6.1 PROJECT BACKGROUND

The project was conducted on behalf of the Lyttelton Borough Council and the North Canterbury Catchment Board with the principal objective to locate and delineate the groundwater resource in the Diamond Harbour area, and if possible, to quantify the available water resources in the area.

The pipeline from Lyttelton that currently supplies the Diamond Harbour township is due for repair or replacement in the near future. It was hoped, as a result of this investigation to determine whether a local groundwater or surface water resource could be used to replace or, at least supplement, the supply from Lyttelton.

6.2 HYDROGEOLOGIC MODELS OF VALLEY FLOOR AQUIFER SYSTEMS

Two aquifer systems were identified in the lower Purau and Orton Bradley Valleys. The first consists of groundwater contained in alluvial aquifers of both valleys, and the second consists of groundwater found in fractured bedrock aquifers within the volcanic formations of Diamond Harbour. The two systmes were found to be intimately related to each other.

Two aquifers were indentified within the alluvial sediments of the Purau Valley. The first gravel layer was found to consist of an infilled river channel (or channels) of 3.78m thickness immediately overlying volcanic bedrock, and is referred to as the Lower Purau Aquifer. A second gravel layer found within 2m of the surface was found to be water bearing within 200m of the coast in the Purau Valley, and is referred to as the Upper Purau Aquifer.

Isotopic data indicates that the waters of the two Purau aquifers is likely to be locally derived meteoric waters of a minimum mean residence time of 50 years.

A single gravel unit is indentified in the Orton Bradley Valley and a few shallow (<2m deep) wells exist indicating this gravel is water bearing near the coast.

6.3 GEOPHYSICAL SURVEY

Three wells (Nos. 6, 12 and 14) in the Purau Valley were geophysically logged using caliper and nuclear logging tools. Correlation of these geophysical logs with the known drill hole logs has enabled the writer to deduce the character and distribution of sediments in the lower part of the Purau Valley.

Resistivity surveys were carried out in the Purau and Orton Bradley Valleys. The aim of this survey was to locate and delineate the two gravel units known to be found in the Purau Valley, and if possible locate similar gravel units in the Orton Bradley Valley. It was found that the resistivity method could define the Upper Purau Aquifer and a similar aquifer in the Orton Bradley Valley, but it was not possible to locate or determine the extent of the Lower Purau Aquifer using this method.

Volcanic bedrock could be located at most sounding sites and as a result the bedrock profile of the lower Purau Valley was determined.

6.4 HYDRAULIC MODELLING

A single constant rate pump test was carried out on the Lower Purau Aquifer using two wells located within the Purau Motor Camp. Analysis of pump test data revealed that the aquifer was of limited extent and possessed two boundaries. Stallmans method was used to determine the boundary configuration of the Lower Purau Aquifer. Computer simulations showed that two boundaries existed within this aquifer and that these were located 14 and 50m from the pumped well.

A transmissivity of $11.92m^2$/day and a storativity of 3.87×10^{-4} were calculated for the Lower Purau Aquifer.

6.5 DEEP CIRCULATING GROUNDWATER

Studies indicate that deep circulating groundwaters are the main source of recharge for the alluvial groundwater found in the Purau and Orton Bradley Valleys. Deep circulating groundwater exits at the surface as the Sulphur Spring (Purau Valley) and from the 220m deep well (Orton Bradley Valley).

Chemical and isotopic studies indicate that these deep circulating groundwaters are mildly thermal and are of local (ie Banks Peninsula) meteoric origin with mean residence times of 50 years.

Water balance calculations indicate thet 3.6% of precipitation was lost to recharge groundwater over the period 22/1/88 to 4/8/88.

6.6 HIGH ALTITUDE SPRINGS

Of the 300 springs of all discharge magnitudes, the majority of high and medium discharge springs are to be found in the Herbert Peak and Orton Bradley Formation Lavas.

An experiment involving continuous flow gauging of a known bedrock (type 3) perennial spring for a period of 34 days was carried out in the upper Purau Valley. Daily oxygen-18 samples were taken from the spring along with daily precipitation recording and sampling. Two tritium samples were taken from this spring seven months apart.

An exponential-piston flow model with exponential volume three times that of the piston flow volume, was found to represent the age distribution of spring X1a groundwaters. The age of these waters was found to be 10 to 25 years. The lack of significant change in oxygen-18 ratios also indicated that a well mixed reservoir system existed, and this was found to be consistent with the exponential-piston flow model proposed. The oxygen-18 ratios of spring X1a groundwaters were found to be typical of Banks Peninsula spring waters precipitated at moderate altitude. Chemical data indicates that the water of most High Altitude Springs is fit for domestic use. The only treatment necessary in some cases is aeration to bring pH levels to within acceptable limits.

Evidence from this spring experiment suggests that the increase in the flow magnitude related to storm events from a bedrock spring, is almost entirely derived from 'old' stored groundwater and that an infiltration-"head"/storage capacity model is consistent with the observed results. Superimposed on this event variability is a seasonal discharge variability related to seasonal rainfall patterns.

6.7 MANAGEMENT IMPLICATIONS

Four water resource options are available for the development of a 'town supply' water resource in the Diamond Harbour area. These include:

1) Purau and Orton Bradley River waters.
2) Valley-floor alluvial groundwater.
3) High Altitude springs.
4) Deep groundwater stored in bedrock aquifers.

Currently, all the above resources are being utilized to a small degree in the Purau and Orton Bradley Valleys. River water is being used for irrigation on an irregular basis. While alluvial groundwater up to $30m^3/day$ is extracted from the Lower Purau Aquifer. Minor amounts of groundwater (a few tens of cubic metres/day) from other alluvial aquifers in both the Purau and Orton Bradley Valleys is also being utilized for irrigation and domestic use. Some residents and farmers have small schemes involving the development of a few perennial High Altitude Springs for stock and domestic drinking water. Direct pumping from the Sulphur Spring is the only known attempt to develop deep circulating groundwater.

Development options include pumping from both rivers to storage tanks located in Diamond Harbour and possible damming of either river to create artificial reservoirs; pumping of alluvial groundwaters to storage tanks in Diamond Harbour; development of individual perennial High Altitude Springs or damming spring fed tributary streams in the Upper Purau and Orton Bradley Valleys; or attemping to improve yields from deep circulating groundwaters by further drilling.

A safe yeild from all water resource options of between 660 and 1300m^3/day was calculated for the Diamond Harbour area. This figure also allows for the maintenance of acceptable river baseflows in both rivers.

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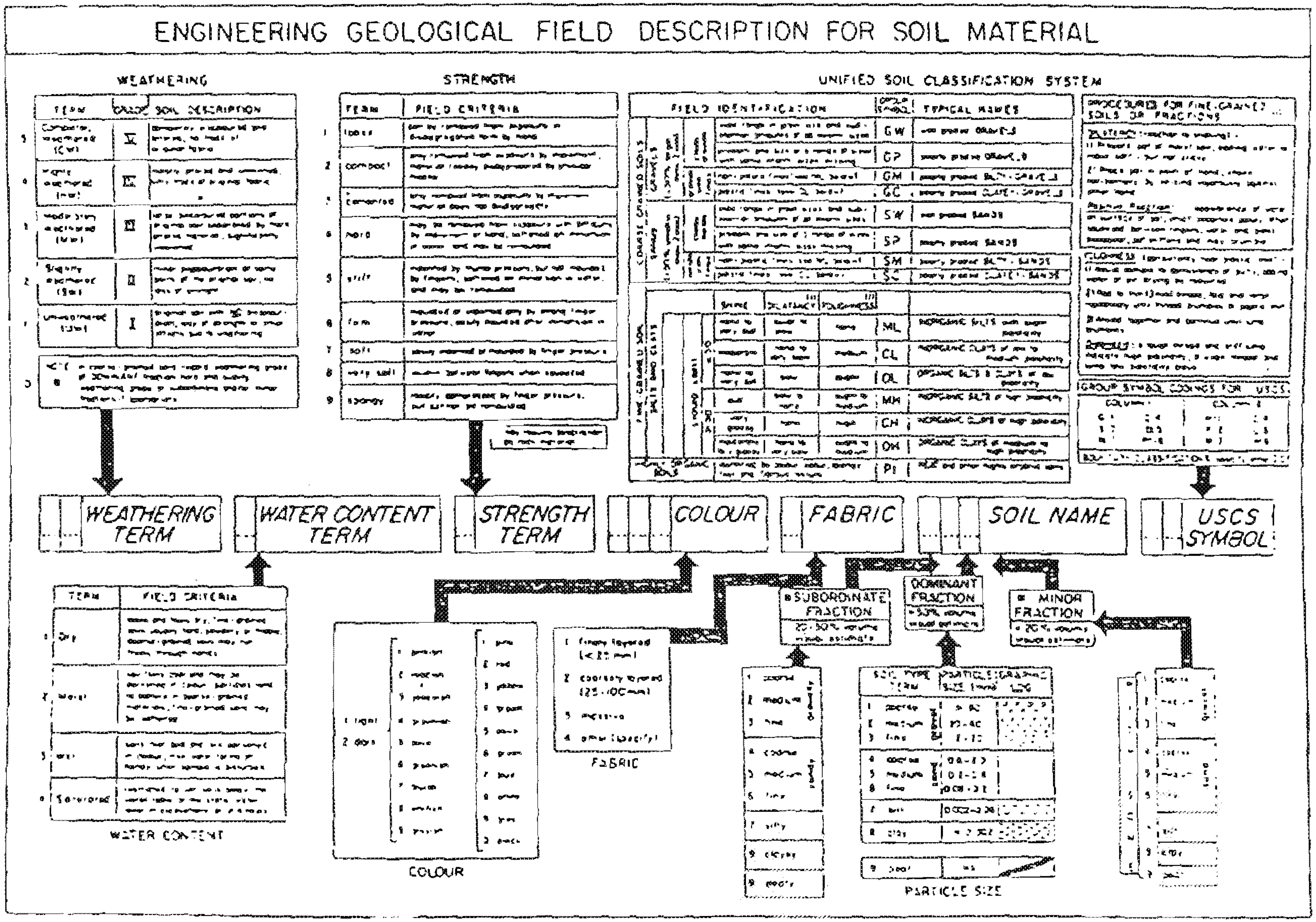
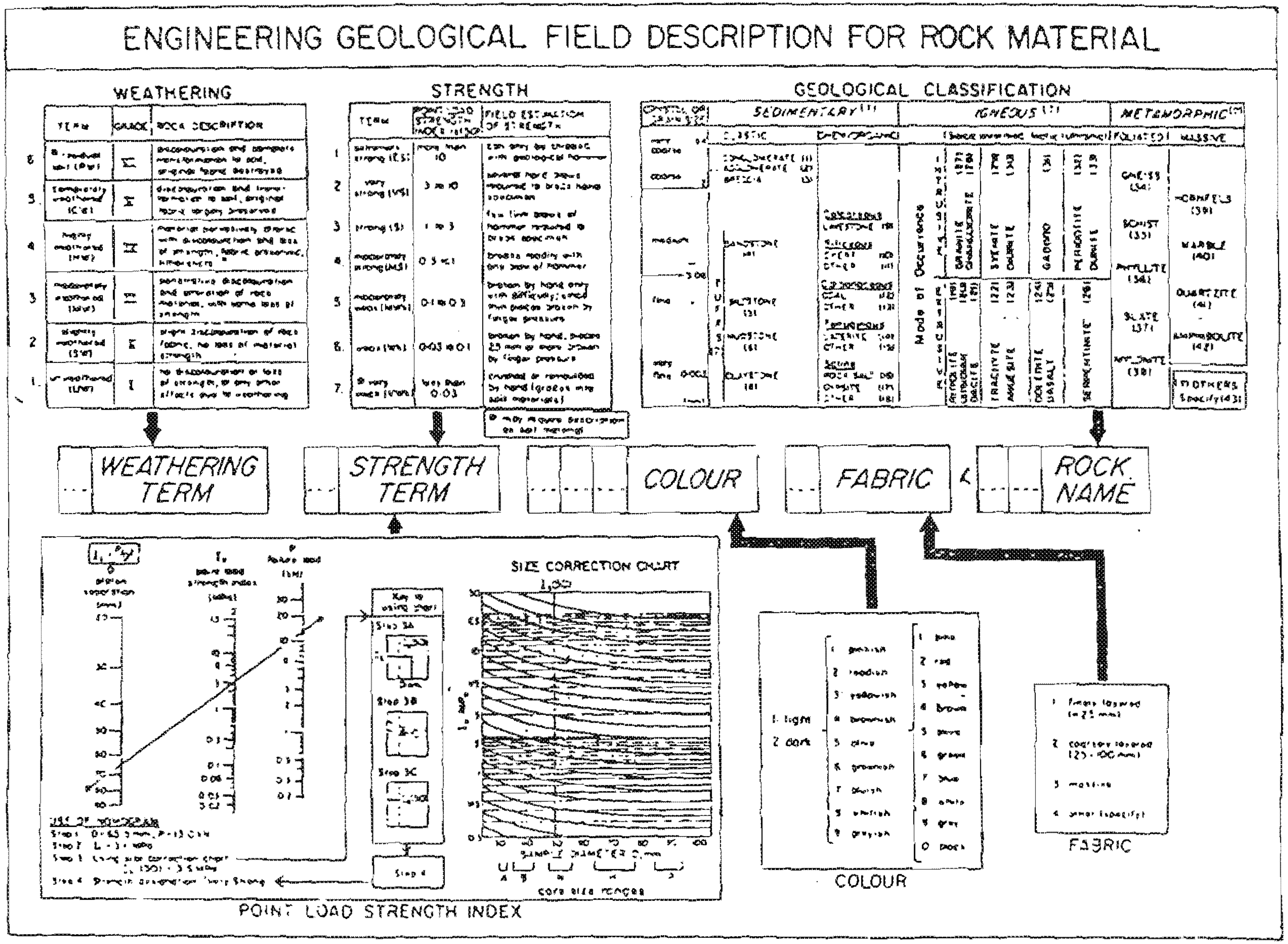
APPENDIX ONE

ROCK AND SOIL MATERIAL DESCRIPTION


ENGINEERING GEOLOGICAL FIELD DESCRIPTION FOR SOIL MATERIAL
WEATHERING
STRENGTH
UNIFIED SOIL CLASSIFICATION SYSTEM
WEATHERING TERM
WATER CONTENT TERM
STRENGTH TERM
COLOUR
FABRIC
SOIL NAME
USCS SYMBOL
SUBORDINATE FRACTION
DOMINANT FRACTION
MINOR FRACTION
WATER CONTENT
COLOUR
FABRIC
PARTICLE SIZE
GW
GP
GM
GC
SW
SP
SM
SC
ML
CL
OL
MH
CH
OH
Pt



ENGINEERING GEOLOGICAL FIELD DESCRIPTION FOR ROCK MATERIAL
WEATHERING
STRENGTH
GEOLOGICAL CLASSIFICATION
SEDIMENTARY
IGNEOUS
METAMORPHIC
WEATHERING TERM
STRENGTH TERM
COLOUR
FABRIC
ROCK NAME
SIZE CORRECTION CHART
COLOUR
FABRIC
POINT LOAD STRENGTH INDEX

ENGINEERING GEOLOGICAL FIELD DESCRIPTION FOR ROCK MASS

FIELD SKETCH OR ANNOTATED PHOTOGRAPH

SCALE — ORIGINAL SCALE — SKETCH ORIENTATION

GENERAL INFORMATION

PROJECT/AREA
LOCALITY

REFERENCE MAP
COORDINATES
ELEVATION

GEOLOGY BY
DATE
CHECKED
Sheet No. of

SHEET REFERENCE

ADDITIONAL DATA

ROCK MATERIAL DESCRIPTION

GRAPHIC SYMBOL	ROCK UNIT No.	WEATHERING	STRENGTH	COLOUR	FABRIC	ROCK NAME
	1					
	2					
	3					
	4					
	5					
	6					

OTHER MATERIAL DESCRIPTIONS (specify)

	7	
	8	
	9	

TERMINOLOGY FOR COMMON DEFECTS IN ROCK MASS

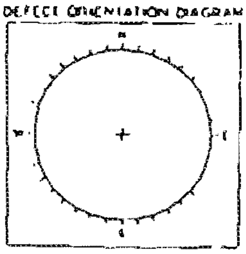
DEFECT TYPE	LAYERING (1): BEDDING (a)	FOLIATION (2)	CLEAVAGE (3)	FRACTURES AND FRACTURE ZONES (1): JOINT/FAULT (4)	SHEARED ZONE (5)	WEAK SEAMS OR ZONES (1): CRUSHED (6)	DECOMPOSED (7)	INFILLED (8)
DESCRIPTION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

(9) OTHERS Specify (9)

DEFECT DATA SUMMARY TABLE

ROCK UNIT No.	DEFECT SET No.	DEFECT TYPE	DEFECT SPACING	DEFECT PERSISTENCE	AV. UNIT BLOCK SIZE	DEFECT ORIENTATION: DIP DIRECTION	DIP	GROUND WATER	REMARKS

DEFECT ORIENTATION DIAGRAM



DEFECT SPACING

	TERM	SPACING (mm)
1	extremely wide	> 2000
2	very wide	600 - 2000
3	wide	200 - 600
4	medium	60 - 200
5	close	20 - 60
6	very close	6 - 20
7	extremely close	< 6

DEFECT PERSISTENCE

	TERM	LENGTH (m)
1	very large	> 10
2	large	3 - 10
3	medium	1 - 3
4	low	0.3 - 1
5	very low	< 0.3

AVERAGE UNIT BLOCK SIZE

	TERM	[illegible]	[illegible]
1	very large		> 10
2	large	[illegible]	0.1 - 1.0
3	medium	[illegible]	0.003 - 0.1
4	small	[illegible]	
5	very small	[illegible]	< [illegible]

GROUNDWATER

	TERM	FLOW RATE
1	dry	
2	seepage	< 1 [illegible]
3	very low flow	1 - 10 [illegible]
4	low flow	10 - 100 [illegible]
5	moderate flow	[illegible]
6	large flow	[illegible] 10 [illegible]
7	very large flow	> 10 [illegible]

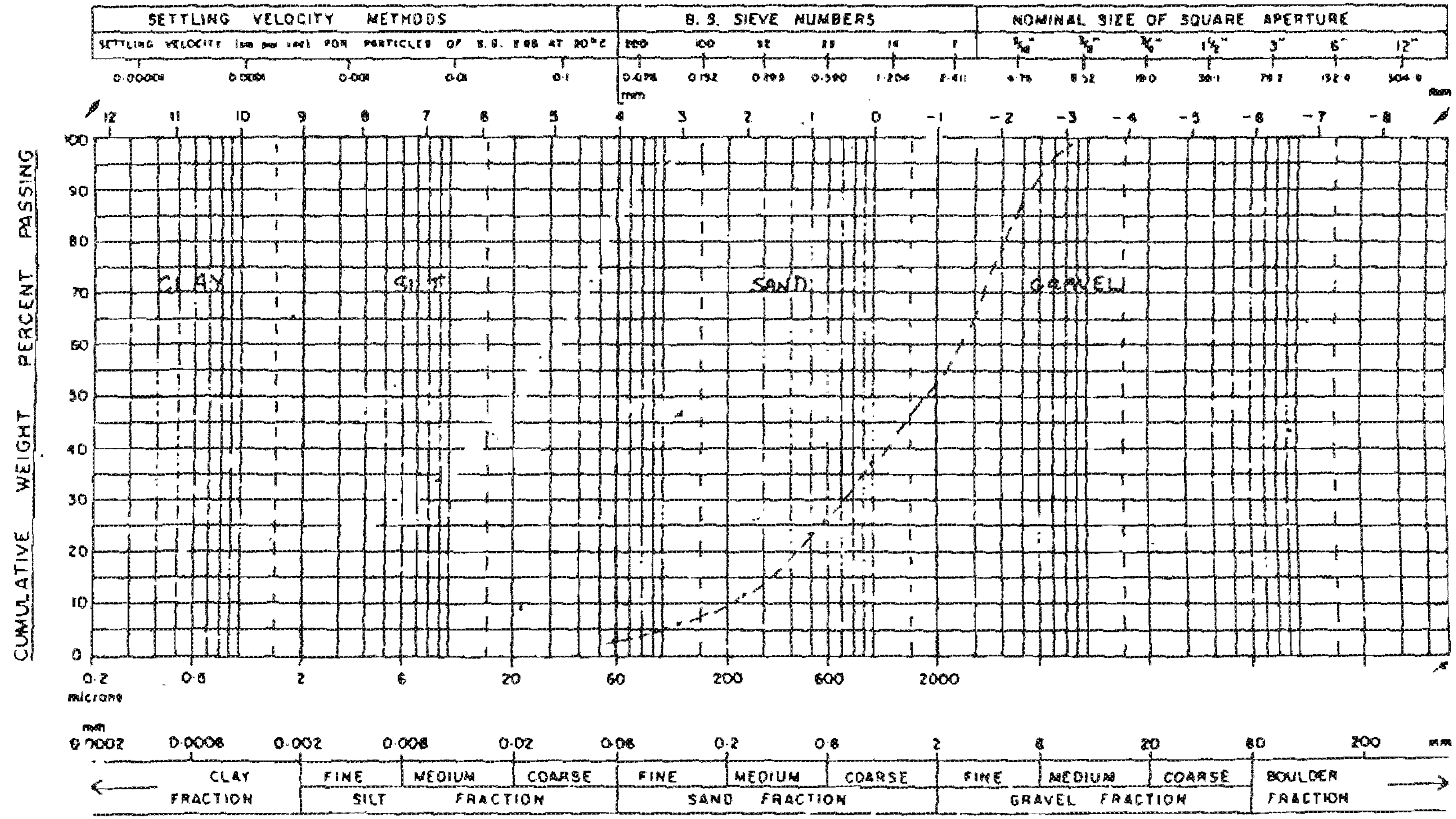
APPENDIX TWO

SIEVE ANALYSES

PARTICLE SIZE DISTRIBUTION — SEMI LOG PLOT

PROJECT HYDROGEOLOGY OF DIAMOND HARBOUR SAMPLE NO Lower Pirau Aquifer SAMPLED BY S.K. PARKER ANALYSED BY S K PARKER

LOCATION PIRAU VALLEY DATE .... DATE ....



PARTICLE SIZE AND CLASSIFICATION

PARTICLE SIZE DISTRIBUTION — SEMI LOG PLOT

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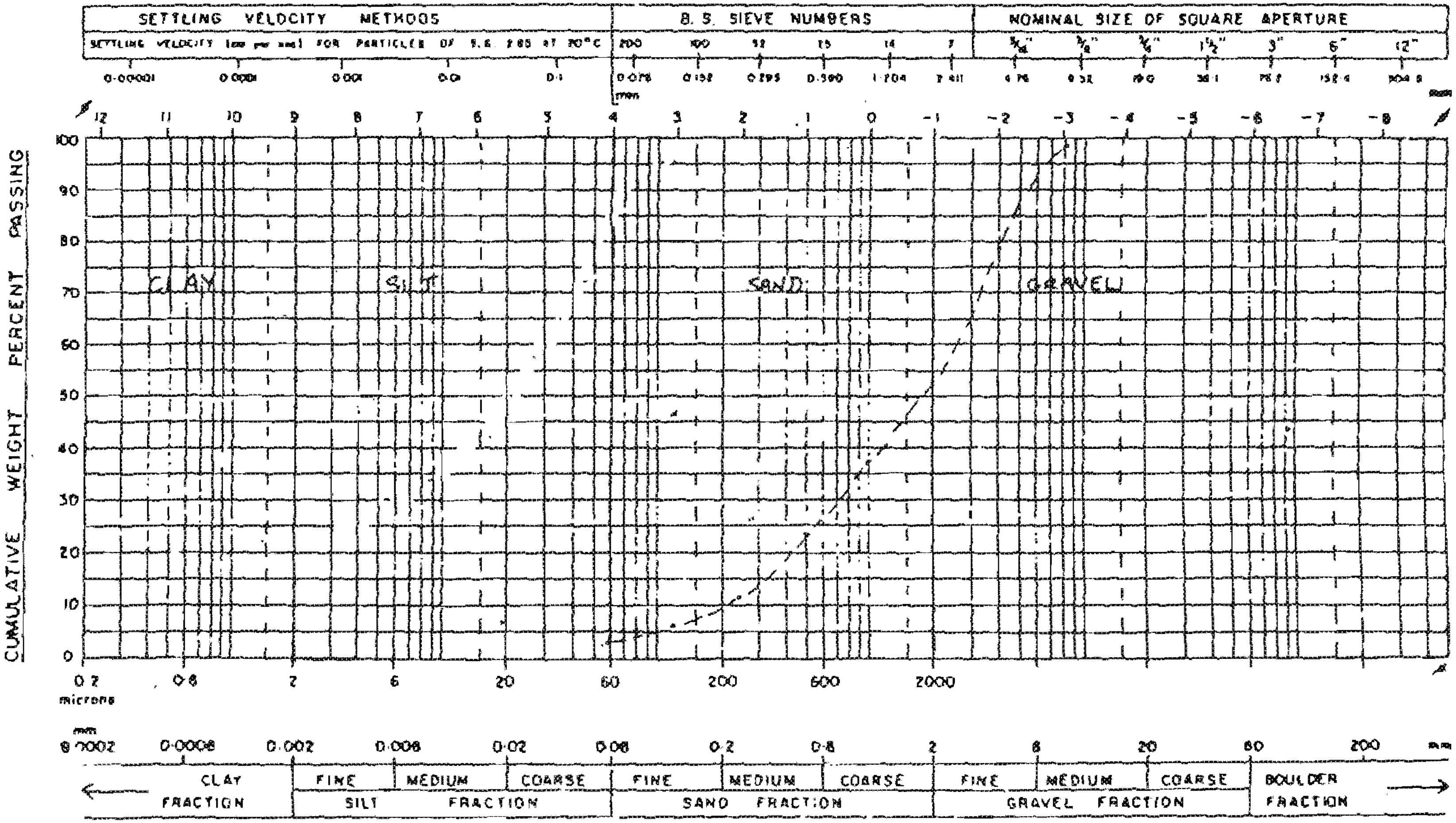
LOCATION Purau Valley DATE .... DATE ....



PARTICLE SIZE AND CLASSIFICATION

APPENDIX THREE

RESISTIVITY ANALYSIS

APPENDIX THREE

A3.1 RESISTIVITY MEASUREMENT

Earth resistivities can be maesured using an array of electrods in contact with the ground. In this investigation only the 'Schlumberger' array has been used.

A direct current generator is used to pass a current, I_{AB}, between the current electrodes A and B (Figure A3.1). The resulting potential difference, ΔV_{MN}, is measured between potential electrods M and N.

When the measuements are made on a flat surface over ground of variable resistivity and the electrodes are point contacts, then apparent resistivity is related to $*V_{MN}$ and I_{AB} by the expression.

$$\rho a = \frac{\pi}{MN} \left[\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2 \right] \frac{\Delta V_{MN}}{I_{AB}} \quad \Omega m$$

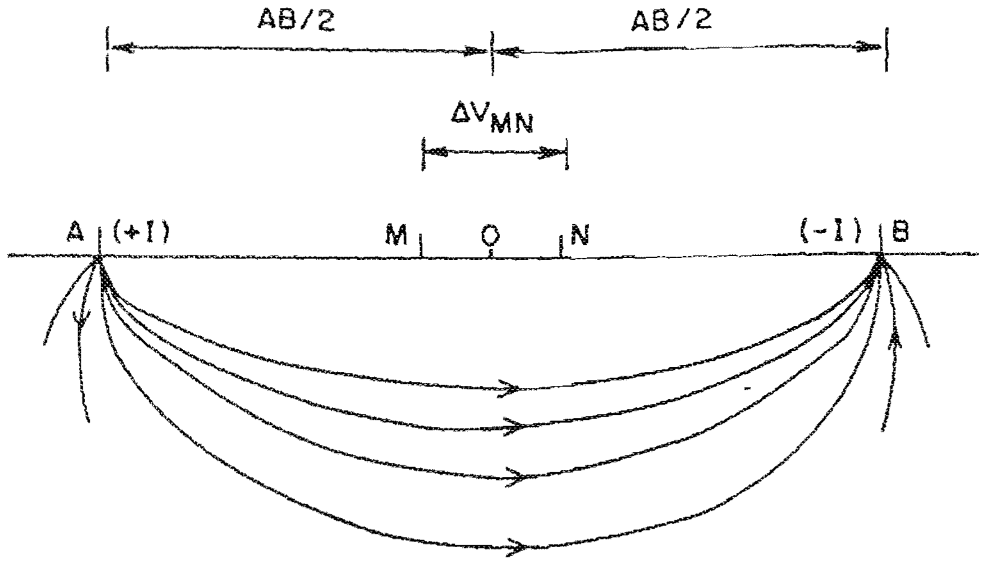
where $MN \leqslant AB/5$ and,

AB,MN = distance (m) between A and B, and M and N respectively.

Apparent resistivity represents a complex average of the resistivities in the ground. Measured apparent resistivity is equal to true ground resistivity when the gound is of uniform resistivity.

The depth and lateral extent of the sample of ground which contributes significantly to apparent resistivity increases as the spacing between the current electrodes increases. Variations of apparent resistivity with electrode spacing can be interpreted in terms of a subsurface distribution of true resistivities (White, 1985).

The advantage of the Schlumberger electrode configuration is that only the current electrodes need to be



O Mid point of A and B and of M and N

A, B Current electrodes

M, N Potential electrodes

AB/2 Distance from centre of array to outside current electrode

ΔV_{MN} Voltage drop between M and N

→ Lines of current flow within the ground between A and B

I Current between A and B

Fig. A3.1 Schlumberger electrode array and schematic current distribution within the ground. (From White, 1985) moved for each measurement. The potential electrodes are only moved when the ratio AB/2 to MN is outside the range 3/1 and 30/1. The use of this configuration is fast, economical and accurate (Soil Test Manual, 1979).

A3.2 INTERPRETATION TECHNIQUES

Preliminary interpretation involves the use of two-layer standard resistivity curves appropriate for the Schlumberger array actually used in the field. Briefly, the procedure used is as follows; (Broadbent, 1984):

A plot of field apparent resistivities on log-log paper is superimposed on a sheet containing the standard curves, making sure that at all stages parallelism between the axes of field and standard sheets is maintained.

The first part of the field curve (ie low AB/2 values, up to the first obvious break in the slope of the curve) is moved so it overlies a similarly shaped and sloping standard curve. The position of the origin (O_1) of this standard curve is marked on the field sheet (Fig. A3.2). The position of O_1 on the resistivity scale (ie the Y-axis) corresponds to layer One resistivity, P_1, and on the AB/2 scale (ie the X-axis) to the depth, d_1, of the boundary between P_1 and P_2 (Fig. A3.2).

Attention is now addressed to the next portion of the field curve that is usually of a different slope compared to the first section of the curve. The procedure above is repeated until a match for this section of curve is found and the origin of the standard curve is marked. Thus, layer two's resistivity, P_2, is established along with its depth, d_2.

The process is repeated until the entire field curve has been treated as above. Four this study initial interpretations were then run through the Geophysics Division (DSIR) computer programme SREINS to establish

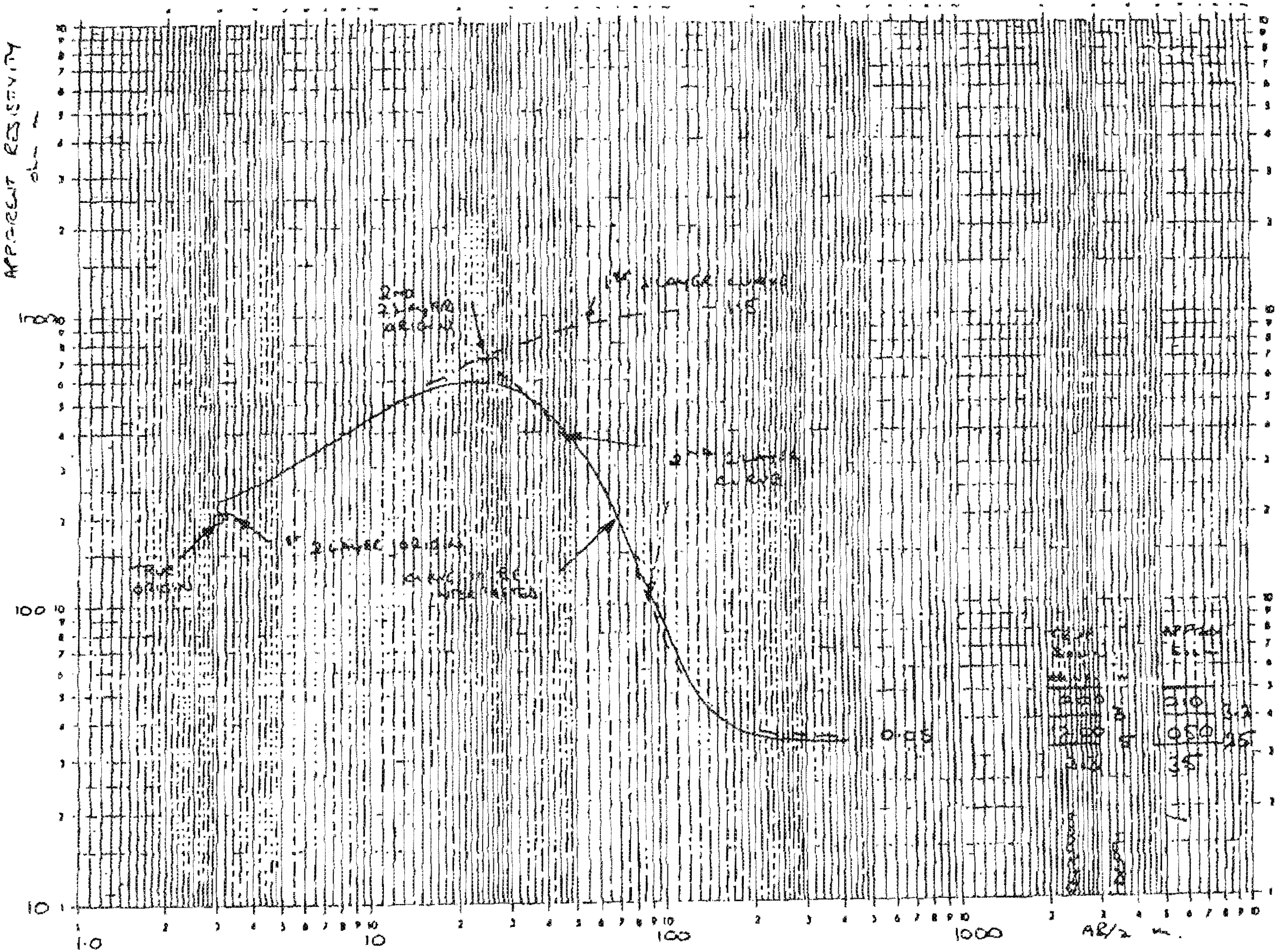
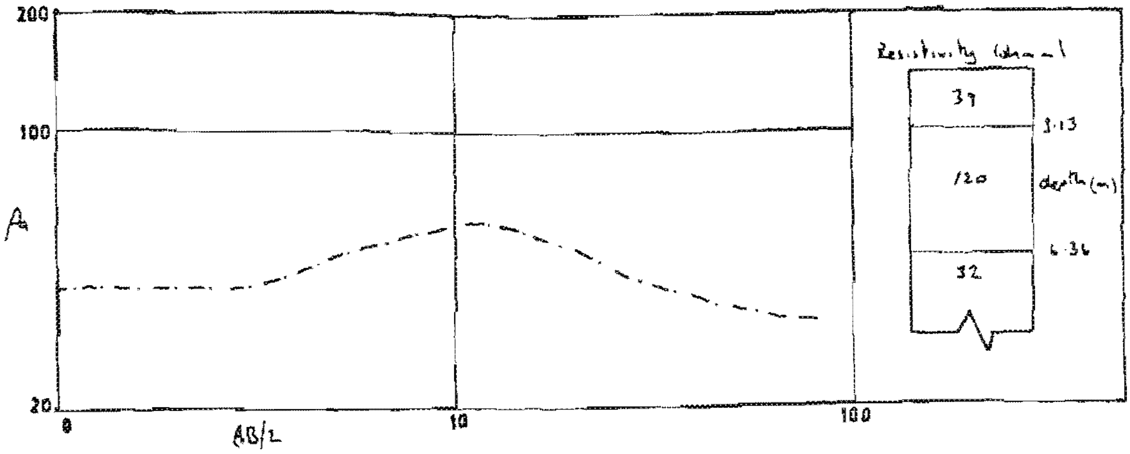


Fig. A3.2 Example of a preliminary interpretation of a resistivity sounding.

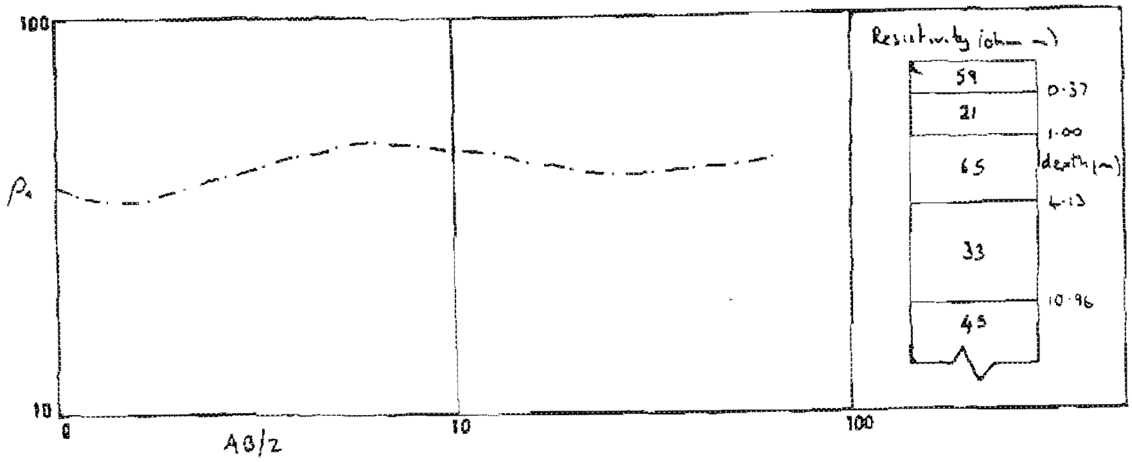
whether the preliminary interpretation was accurate. If the error calculated on the curve fit was more than 5%, then a re-interpretation of the field data was necessary and so the whole process repeated.

The interpretations calculated for the 15 soundings conducted during this investigation are represented in the following section.

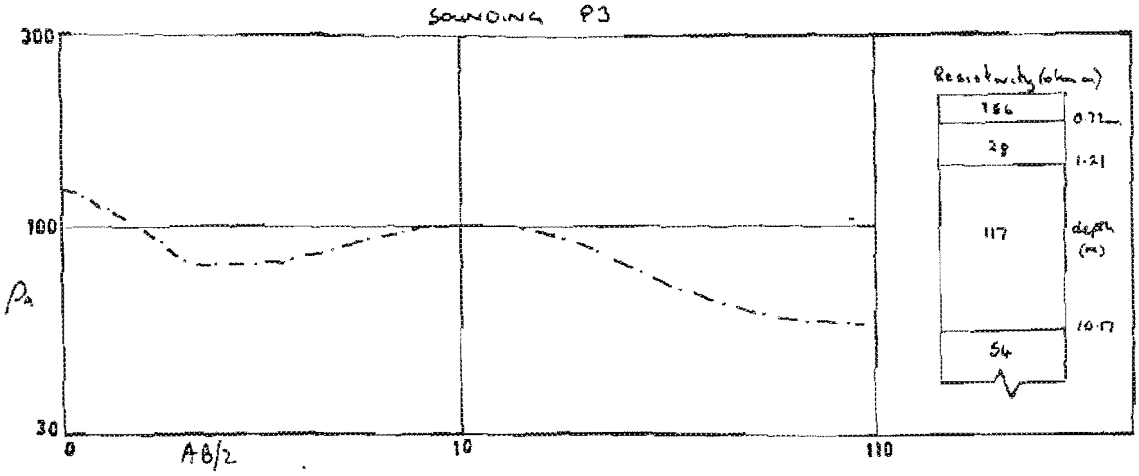
SOUNDING P1



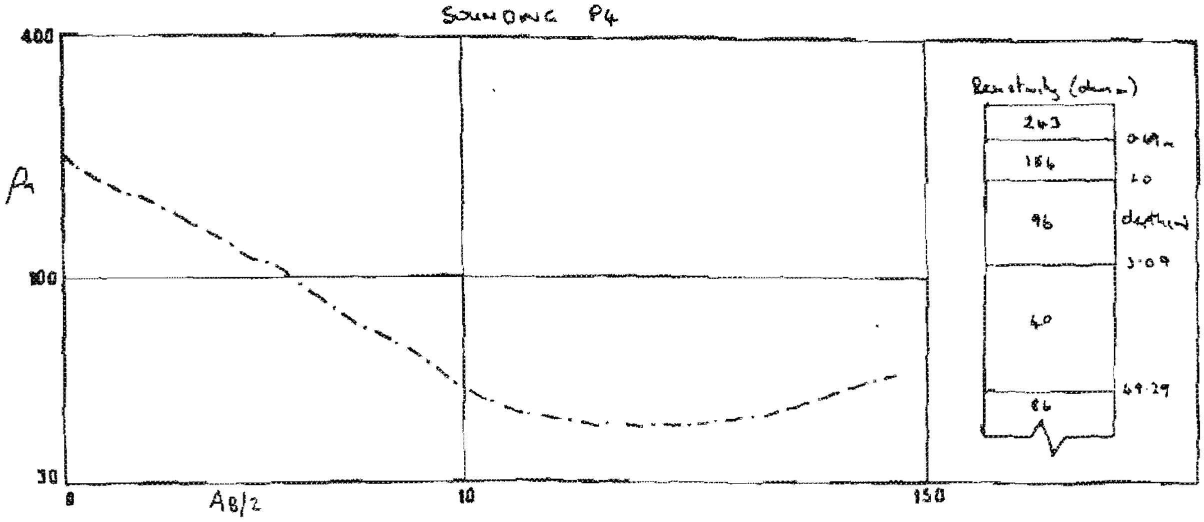
SOUNDING P2

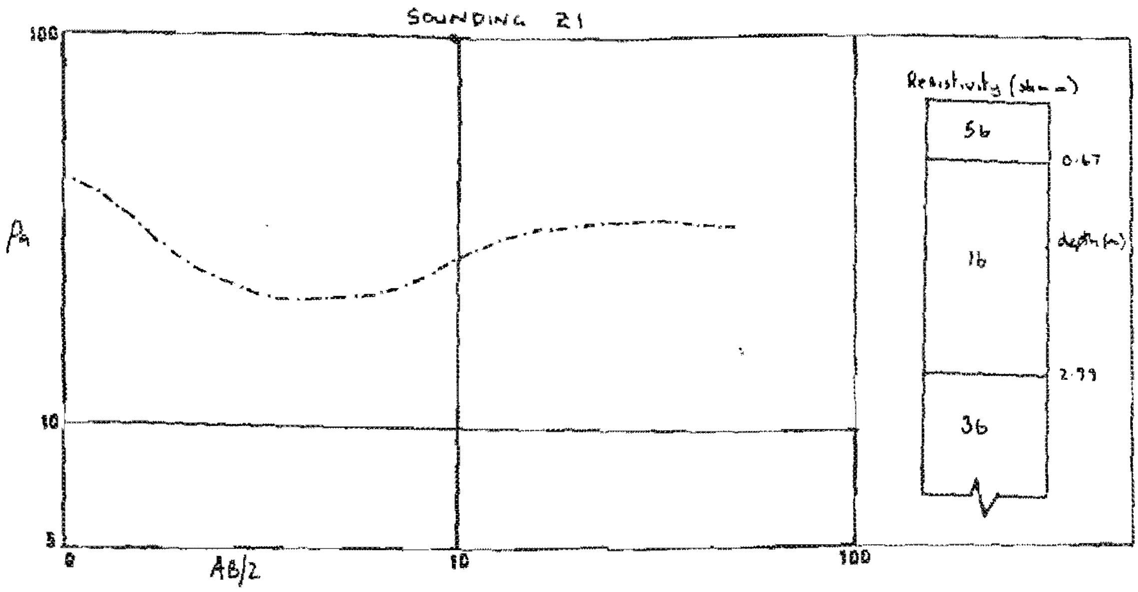


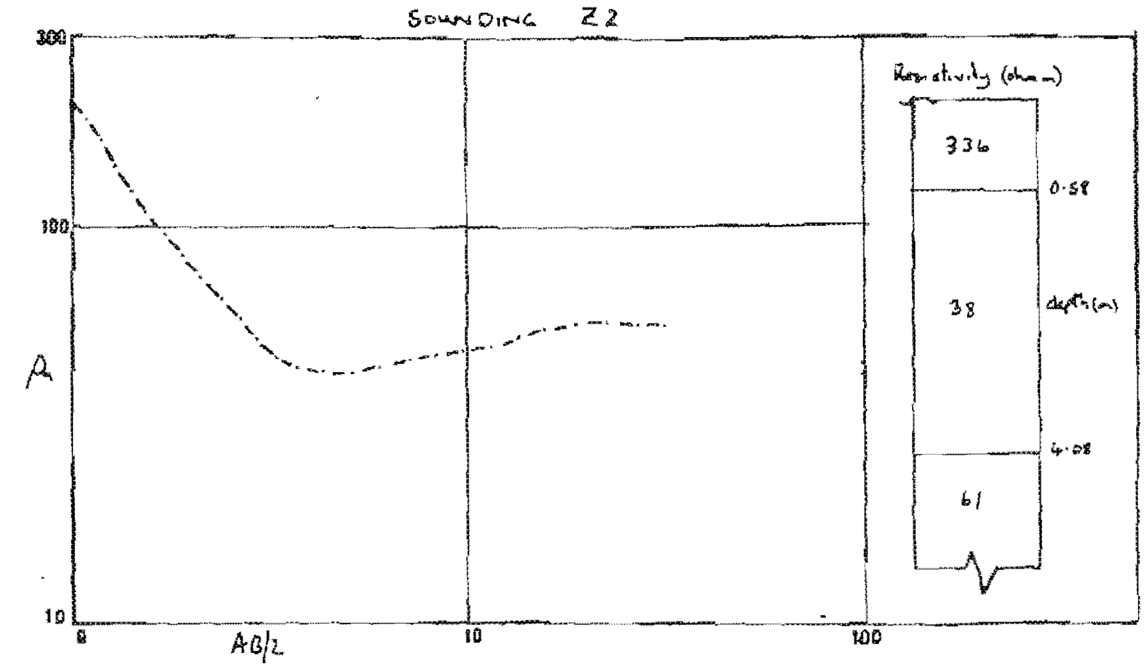
SOUNDING P3

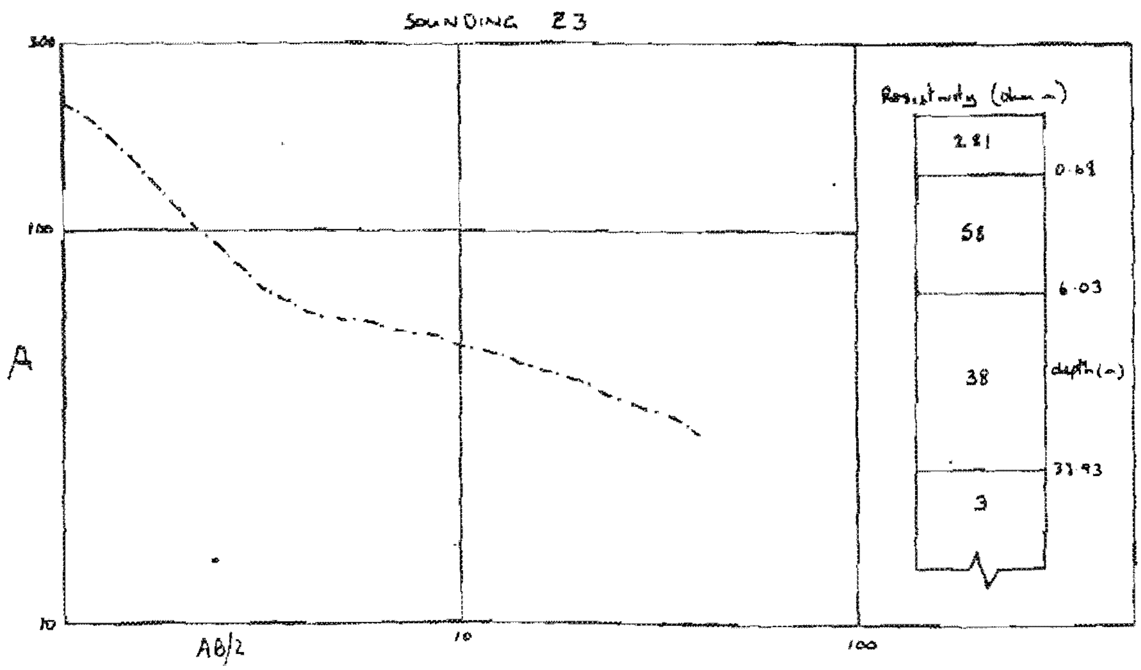


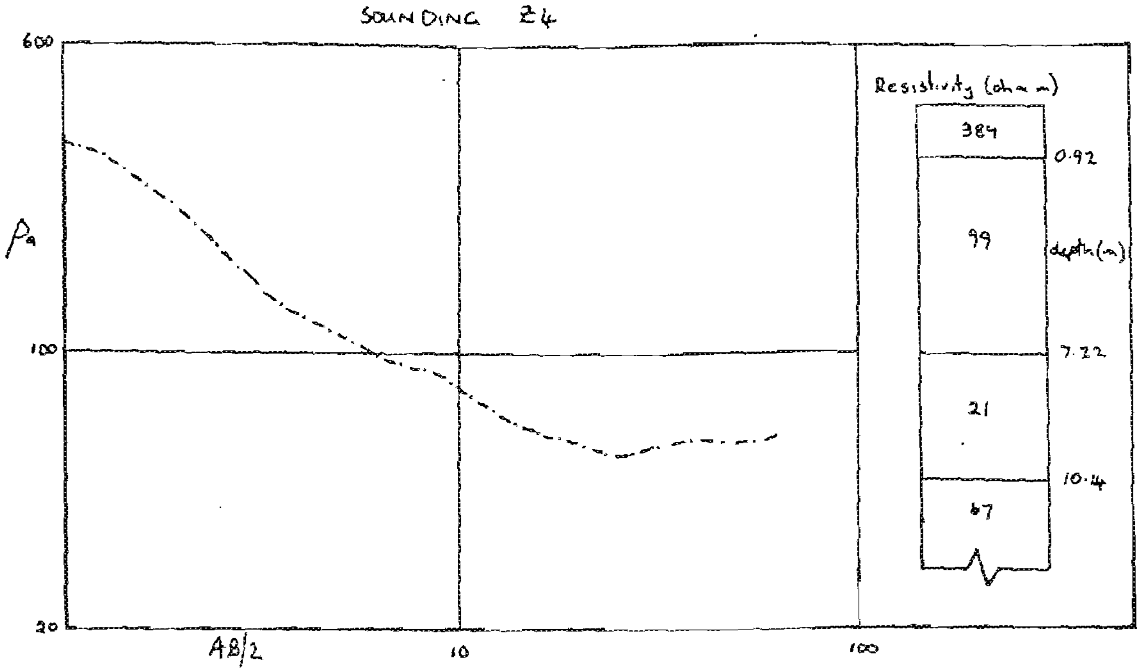
SOUNDING P4

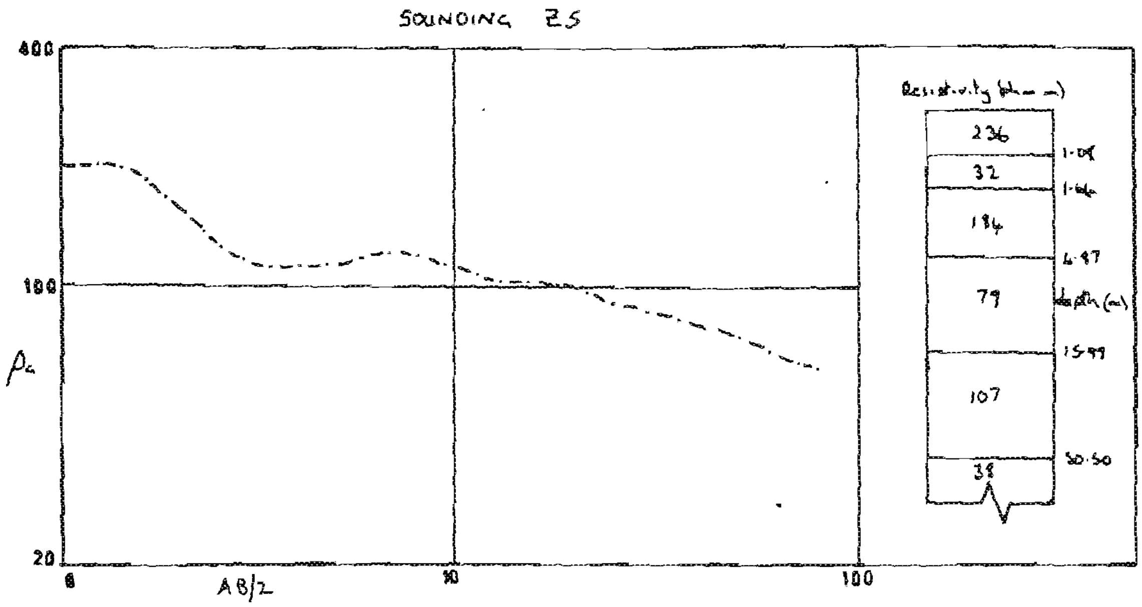


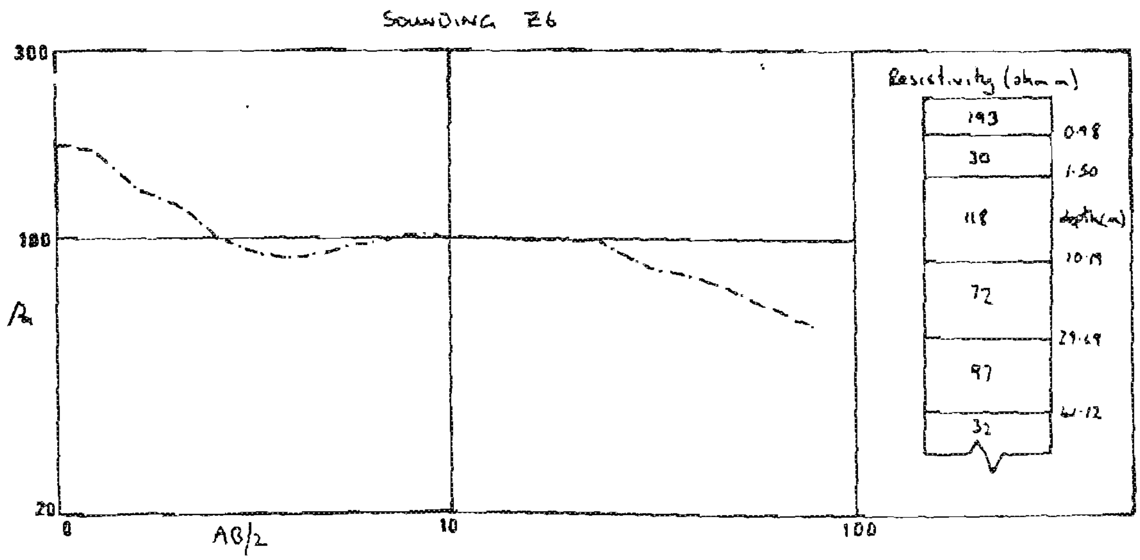

SOUNDING Z1
Resistivity (ohm-m)
56
0.67
16
depth (m)
2.99
36
AB/2

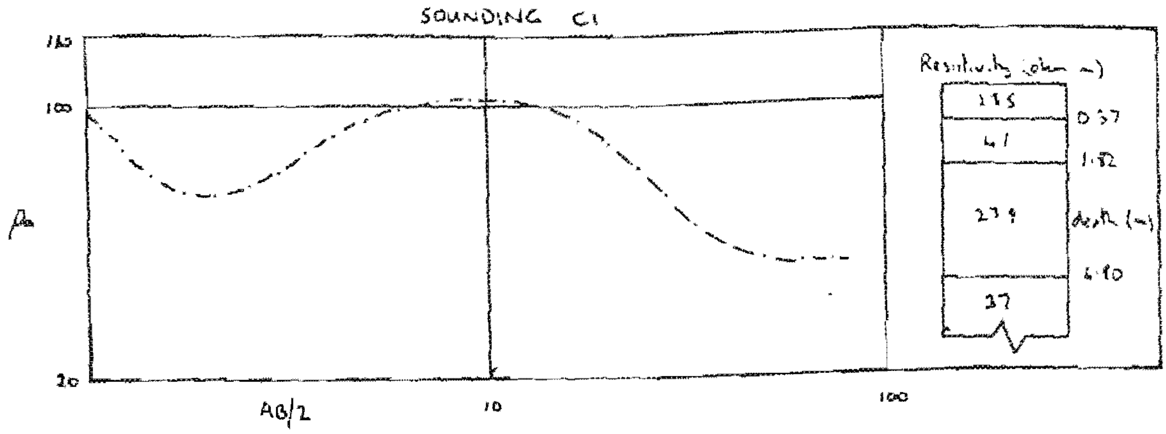

SOUNDING Z2
Resistivity (ohm-m)
336
0.58
38
depth (m)
4.08
61
AB/2

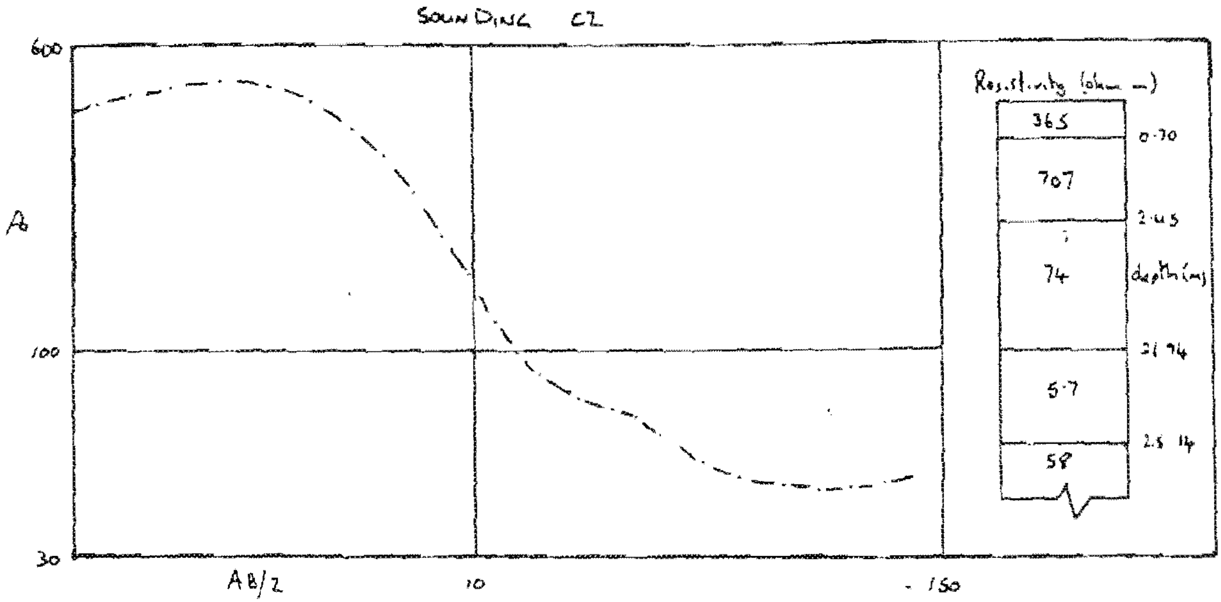

SOUNDING Z3
Resistivity (ohm-m)
281
0.68
58
6.03
38
depth (m)
33.93
3
AB/2

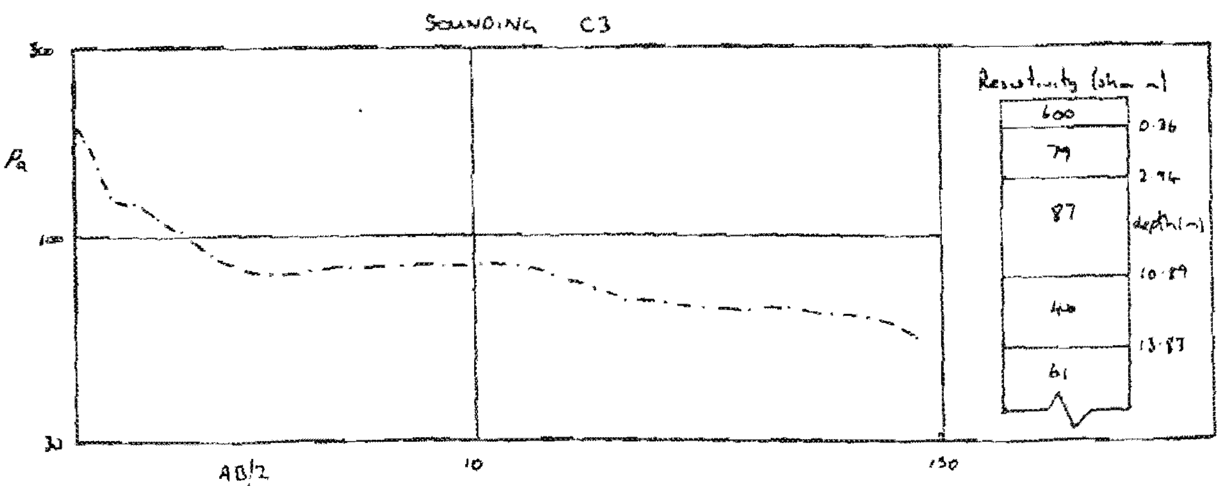

SOUNDING Z4
600
100
20
ρ_a
AB/2
10
100
Resistivity (ohm m)
384
99
21
67
0.92
depth (m)
7.22
10.4


SOUNDING Z5
400
100
20
ρ_a
AB/2
10
100
Resistivity (ohm m)
236
32
184
79
107
38
1.08
1.64
4.97
depth (m)
15.99
50.50

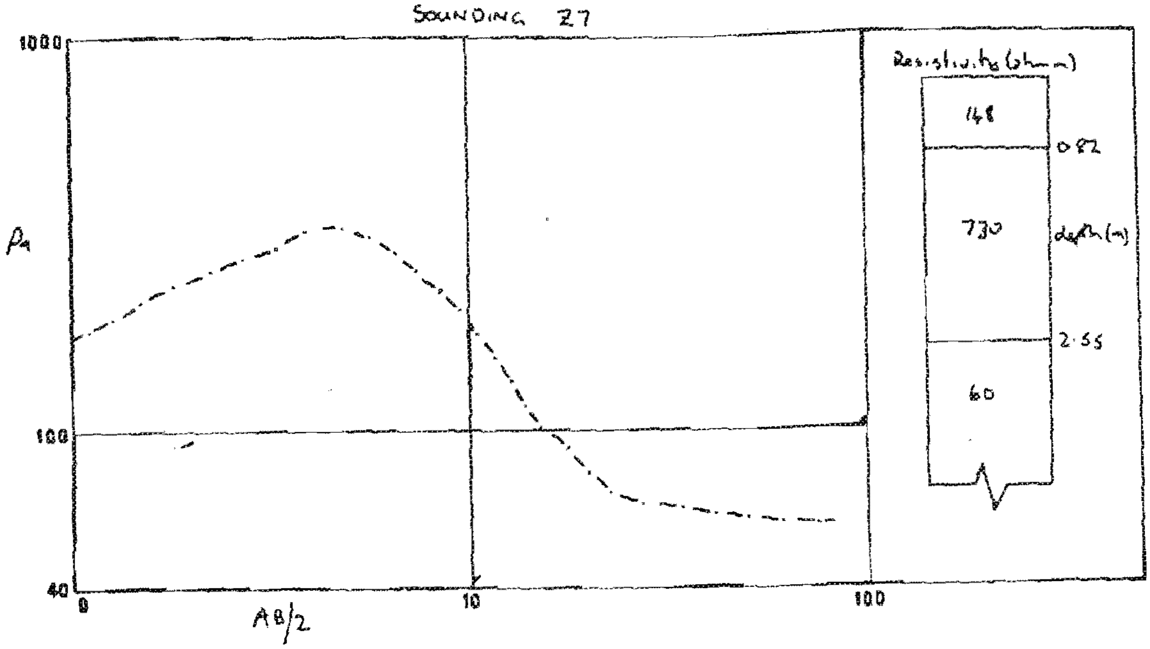

SOUNDING Z6
300
100
20
ρ_a
AB/2
10
100
Resistivity (ohm m)
193
30
118
72
97
32
0.98
1.50
depth (m)
10.19
29.69
61.12


SOUNDING C1
Resistivity (ohm m)
135
41
279
37
0.37
1.82
depth (m)
6.90
AB/2
10
100
20
100

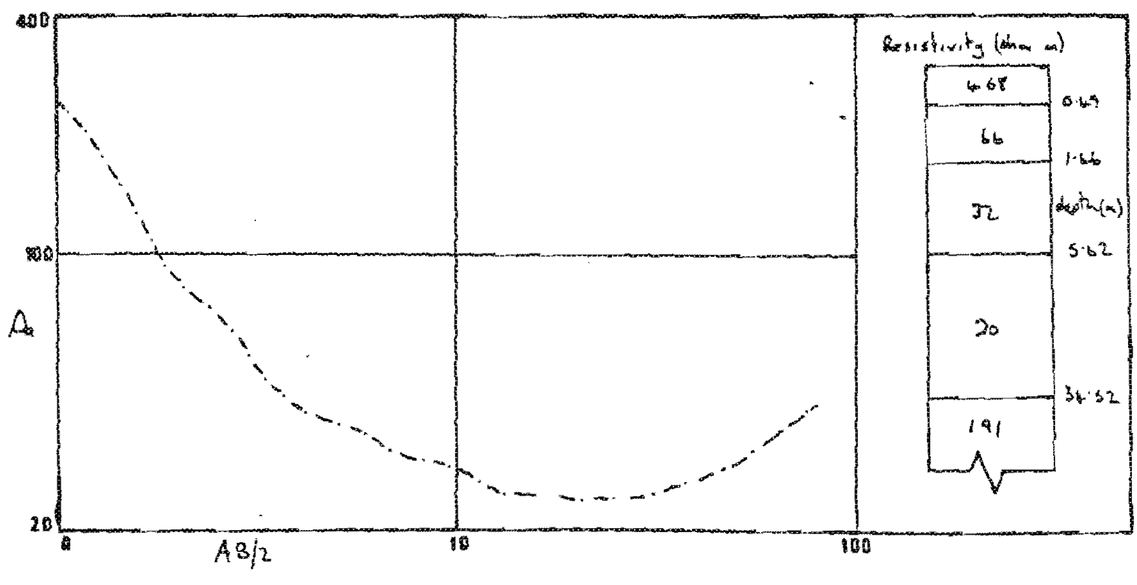

SOUNDING C2
Resistivity (ohm m)
365
707
74
57
58
0.70
2.45
depth (m)
21.94
25.14
600
100
30
AB/2
10
150


SOUNDING C3
Resistivity (ohm m)
600
79
87
46
61
0.36
2.94
depth (m)
10.89
13.87
300
100
30
AB/2
10
150

SOUNDING 27



SOUNDING 28



APPENDIX FOUR

GEOPHYSICAL LOGGING

A4.1 Caliper Log

A4.2 Natural Gamma Log

A4.3 Gamma-Gamma Log

A4.4 Neutron-Neutron Log

APPENDIX FOUR

A4.1 CALIPER LOG

The caliper sonde is a tool about two metres in length with three spring tensioned feelers at the base. The feelers are adjusted to the casing internal diameter and are allowed to move in and out as the tool is raised from the base of the hole. A record of the changes in hole internal diameter is obtained. The sensitivity of the tool can be altered to such a degree that even casing welds can be detected.

It is important to have a caliper log of a particular hole to aid in interpreting the other types of logs gained in an investigation. Signal changes in the various nuclear logs may reflect not only lithology changes, but also could be changes in borehole internal diameter.

A4.2 NATURAL GAMMA LOG

In natural gamma logging measurements are made of naturally occurring radiation coming from the materials encountered in the borehole.

Gamma radiation is emitted from certain elements in geological materials that are unstable so that their nuclei decay to a more stable state. Gamma radiation has a great ability to penetrate other materials such as borehole casings.

The principle sources of gamma radiation are the isotopes Thorium^{232}, Potassium^{40} and Uranium^{238}. These isotopes are present in significant quantities in some igneous and metamorphic rocks and also in some sedimentary sequences. Clays and shales usually have high concentrations of, for example potassium, while clean sands and gravels will generally emit lower levels of radiation.

The precise radiation levels emitted, however, will depend on the chemical composition of the detrital material.

A4.3 GAMMA-GAMMA LOG

In gamma-gamma logging, an active source of gamma radiation (in this case Ra^{226}) is lowered into the borehole along with a detector (NaI (Tl) crystal). A space of adjustable length separates the source from the detector so that only back-scattered radiation is detected.

Gamma rays of intermediate energies undergo what is known as Compton scattering and are reflected back towards the detector. As the amount of back-scattered radiation depends on the electron density of the formation, the density log measures the density of electrons in a material rather than the true density of that material. To calculate the true density of a material it is necessary to know the ratio of the atomic number to the mass number. The gamma-gamma log is often referred to as an apparent density log.

A4.4 NEUTRON-NEUTRON LOG

A neutron-neutron tool consists of a source of neutrons (in this case Americium/Beryllium) and a detector (BF_3). A spacer also separates the source from the detector.

In order to be counted by the detector of a neutron-neutron tool, the neutrons must lose most of their energy in collisions with the nuclei of atoms in the borehole fluid and rock strata. It has been shown that a neutron loses more than half its energy in a collision with a particle of similar mass . Consequently, a hydrogen-rich material is by far the most effective in slowing or moderating neutrons, as the mass of a hydrogen nucleus is very nearly equal to the mass of a neutron. Other light elements are effective to a lesser extent at showing neutrons.

As most of the hydrogen in geological materials occurs in water molecules, those materials with a high water content or porosity will absorb more neutrons. Thus, neutron-neutron logging is mainly used as an indicator of apparent porosity.

APPENDIX FIVE

PUMP TEST THEORY

APPENDIX FIVE

A5.1 PUMP TEST THEORY

A5.1.1 Theis Nonequalibrium Well Equation

The simplest form of the Theis equation is:

$$s = \frac{1}{4}\,\frac{Q}{\pi}\,\frac{W_{(u)}}{T}$$

where s = drawdown, in metres at any point in the vicinity of a well discharging at a constant rate
Q = pumping rate, in m^3/day
T = coefficient of transmissivity of the aquifer, in m^2/day

$W_{(u)}$, the well function of u, is an abbreviation for the exponential integral:

$$\int_{u}^{\infty} \frac{e^{-x}}{x}\,dx = W_{(u)} = -0.5772 - \log_e U + \frac{U^2}{2.2!} + \frac{U^3}{3.3!} - \frac{U^4}{4.4!} + \ldots$$

$u = \frac{r^2 S}{4Tt}$ where r = distance, in metres, from the centre of a pumped well to the point where drawdown is measured
S = storage coefficient
t = time, in days

A graphical solution can be worked out for values of T and S if drawdown measurements are available from a least one observation well. The method involves matching a curve plotted from specific pumping test data with a type curve. The type curve is prepared by plotting values of $W_{(u)}$ against 1/u, on graph paper with logarithmic scales. Field data from a pumping test are plotted on similar graph paper with identical scales to the type curve.

The curve of field data is superimposed on the type curve until a good matching position is found. In this case a convenient match point on the graph was found where $W_{(u)}$ and 1/u equalled one. The values of t and s at the point where $W_{(u)}$ and 1/u equaled one were then read off (Fig. 3.9).

Transmissivity (T) and the Storage Coefficient (S) were worked out as follows:

$$T = \frac{1}{4\pi}\frac{Q}{s}W_{(u)} \quad \text{where} \quad Q = 8\text{gal/min} = 52.37\text{m}^3/\text{day}$$
$$s = 0.35\text{m}$$
$$W_{(u)} = 1$$
$$\pi = 3.14$$

therefore, <u>$T = 11.91\text{m}^2/\text{day}$</u>

$$S = \frac{4uTt}{r^2} \quad \text{where} \quad \frac{1}{u} = 1$$
$$T = 11.91$$
$$t = 1.17 \text{ mins or } 8.13 \times 10^{-4} \text{ days}$$
$$r = 10\text{m}$$

therefore, <u>$S = 3.87 \times 10^{-4}$</u>

A5.1.2 <u>Theory of Images and Hydrologic Boundary Analysis</u>

Stallman developed a type curve method of analysing pumping test data obtained during pumping tests in the vicinity of one or more boundaries. In this case boundaries are assumed to be barrier boundaries.

The following assumptions and conditions are made:

1) Within the zone influenced by the pumping test, the aquifer is crossed by one or more straight, fully penetrating barrier boundaries.

2) The aquifer is homogeneous, isotropic and of uniform thickness over the area influenced by the pumping test.

3) Prior to pumping the piezometric surface is nearly horizontal over the area influenced by the pumping test.

4) The aquifer is pumped at a constant discharge rate.

5) The pumped well penetrates the entire aquifer and receives water from the entire thickness of the aquifer by horizontal flow.

As the aquifer is in unsteady state then:

6) The storage in the well needs to be neglected, ie the well diameter is very small.

7) Water removed from storage is discharged instantaneously with decline of head within the well.

8) The aquifer can be confined (as in this case) or unconfined.

The distance between the real pumped well and a piezometer is called r_r, the distance between an imaginary well and the piezometer is called r_i, and their ratio $r_i/r_r = B$.

If $u = \frac{r^2S}{4Tt}$, and $u_i = \frac{r_i{}^2S}{4Tt} = \frac{B^2r_r{}^2S}{4Tt} = B^2u$,

then the drawdown in the piezometer is described by the following equation:

$$s = \frac{Q}{4\pi T}\left(W_{(u)} + W(B_1{}^2u) + W(B_2{}^2u) + \ldots W(B_n{}^2u)\right) - (1)$$

The number of terms in the bracketed part of equation (1) is determined by the number of image wells. If there is only one straight barrier boundary then there are only two terms in equation (1): the term $Q/4TW_{(u)}$ describing the drawdown of the real well and the term $Q/4TW(B^2u)$ describing the drawdown attributable to the image well.

It two parallel straight barrier boundaries are suspected the number of image wells becomes infinite. Kruseman and De Ridder (1970) suggest a limit of where B>100. The influence on the drawdown in the piezometer under consideration is considered to be negligible from an image well at this distance from the real well. It was found that only up to six image wells were required for this analysis (Figs. 3.10 and 3.11).

In fact, the number of image wells needed will to a large degree depend on factors such as the location of suspected boundaries in relation to the real well and piezometers, the distance between piezometers and the real well and the transmissivity of the aquifer. If a relatively low transmissivity is calculated from the drawdown curve before its departure from the ideal curve, then it can be assummed pumping will cause the drawdown cone to have a small radius and steep sides. The effect of this in practice is to reduce the number of image wells needed. In this case, for a two parallel boundary model only six image wells on either side of each boundary were needed.

Hence, for a single barrier boundary Stallmans equation is:

$$s = \frac{Q}{4\pi T} \left(W_{(u)} + W(B_1{}^2u)\right) - (2)$$

and, for a two parallel barrier boundaries:

$$s = \frac{Q}{4\pi T} \left(W_{(u)} + W(B_1{}^2u) + W(B_2{}^2u) + \ldots W(B_6{}^2u)\right) - (3)$$

Procedure

1) The value of Q is known from the pump test, and the value for T is calculated using the early part of the time/drawdown plot by the Theis method. This early data is assummed to represent the true aquifer conditions before any boundary effects cause drawdown to depart from the ideal curve.

2) Determine the appropriate boundary configuration and prepare a plan of the equivalent system of image wells (Fig. 3.11).

3) Determine for the piezometer the value of r_r and values of r_i. Calculate the value(s) of $B = r_i/r_r$ for each image well. Calculate the numerical values of $W(u,B_{1\ \text{to}\ n})$ with respect to values of u according to either equation (2)

or (3). Given a first approximation to the real boundary conditions, plot the values of drawdown(s) verses time. Compare the time/drawdown curve gained with the real time/drawdown curve.

4) Repeat this procedure altering the location of the boundary(ies), and hence the image well configuration until a simulated curve is produced that best fits the field data. This then represents the best approximation to the hydraulic conditions imposed on the well due to the aquifer boundaries.

The following computer programme written by P Callander NCCB, was used to simulate the drawdown caused by two parallel boundaries. A best fit of field data and simulated data was found where boundaries were sited at 14 and 50m from the pumped well (Fig. 3.12 and 3.13). The model produced by the computer simulation suggests the Lower Purau Aquifer is a Strip aquifer of approximately 64m width.

```
C       PROGRAM STRIP.FOR
C
C       A PROGRAM TO CALCULATE DRAWDOWNS USING THE THEIS EQUATION
C       FOR A POINT AT A SPECIFIED DISTANCE FROM A PUMPING WELL
C       AT A VARIETY OF TIMES IN A CHANNEL SHAPED AQUIFER.
C       THE AQUIFER IS MODELLED BY PAIRS OF IMAGE WELLS PUMPING
C       AT THE SAME RATE AS THE ONE REAL WELL.
C       THIS CREATES THE EFFECT OF A STRIP AQUIFER BOUNDED BY TWO
C       PARALLEL IMPERMEABLE BARRIERS.
C
C
C       THIS PROGRAM MUST BE LINKED WITH ,"FUNCTION THEIS"
C
C
C
        INTEGER IN,OUT,FILE,N,I,J,L
        REAL PI,T,S,DISTW,Q,DDOWN,TIME,EXP,TERMW,TERMI,COEFF1,COEFF2,SW,SI
        DIMENSION DISTI(40),X(500),Y(500)
C
        IN=5
        OUT=6
        FILE=10
C
        OPEN(UNIT=FILE,NAME='STRIP.OUT',TYPE='NEW')
C
        PI = 3.14159
C
C       INPUT DATA FROM TERMINAL
C
        WRITE(OUT,1000)
1000    FORMAT('  ENTER ALL VALUES IN S.I. UNITS  ',/
     1         ,'  ENTER TRANSMISSIVITY                : '$)
        READ (IN,1010) T
1010    FORMAT(F10.0)
        WRITE(OUT,1020)
1020    FORMAT('  ENTER STORATIVITY                   : '$)
        READ (IN,1010) S
        WRITE(OUT,1030)
1030    FORMAT('  ENTER DISTANCE FROM PUMPING WELL : '$)
        READ (IN,1010) DISTW
        WRITE(OUT,1040)
1040    FORMAT('  ENTER PUMPING RATE                  : '$)
        READ (IN,1010) Q
        WRITE(OUT,1041)
1041    FORMAT('  ENTER MAXIMUM TIME IN MINUTES (6 DIGITS) :'$)
        READ (IN,9998) KILL
        WRITE(OUT,1042)
1042    FORMAT('  NOW ENTER THE NUMBER OF IMAGE WELLS TO BE USED ')
        READ (IN,9999) N
        DO 1044 I=1,N
           WRITE(OUT,1043)I
1043       FORMAT('  ENTER DISTANCE FROM IMAGE WELL ',I3,'     '$)
           READ(IN,1010) DISTI(I)
1044    CONTINUE.
C
C
C  INITIAL VARIABLES INPUTED
C  OUTPUT THEM TO A FILE
C
        WRITE(FILE,1050) T,S,DISTW,Q
1050    FORMAT(' INITIAL VALUES ENTERED USING S.I. UNITS : ',/,
     1   ' TRANSMISSIVITY                = ',F15.7,/,
     2   ' STORATIVITY                   = ',F15.7,/,
     3   ' DISTANCE FROM PUMPING WELL    = ',F15.7,/,


     4   ' PUMPING RATE                  = ',F15.7,//)
        WRITE(FILE,1051) N
```

```
1051     FORMAT(X,I4,' IMAGE WELLS WILL BE USED : ',/)
         DO 1053 I=1,N
               WRITE(FILE,1052) I,DISTI(I)
1052           FORMAT(X,' IMAGE WELL ',I4,' IS ',F6.1,' METRES FROM',
    1          ' THE OBSERVATION BORE ',/)
1053     CONTINUE
         WRITE(FILE,1054)
1054     FORMAT(//,   '  TIME IN MINUTES      DD DUE TO PUMPING WELL
    1     DD DUE TO MOST DISTANT IMAGE WELL          TOTAL DRAWDOWN  ',/)
C
C
C       CALCULATION OF DRAWDOWNS AT SET TIMES
C
         COEFF1 = Q/(4.0*PI*T)
         COEFF2  = S/(4.0*T*60.0)
         TERMW = DISTW*DISTW*COEFF2
C        SPECIFY TEN POINTS PER LOG CYCLE OF TIME (IN MINUTES)
         DO 20 I = 1,60
             EXP = 0.1*I
             TIME = 10.0**EXP
             IF(TIME.GT.KILL) GOTO 30
             SW = COEFF1*THEIS(TERMW/TIME)
             DDOWN = SW
C         CALCULATE THE EFFECT OF THE IMAGE WELLS
             DO 15 L = 1,N
                TERMI = DISTI(L)*DISTI(L)*COEFF2
                SI = COEFF1*THEIS(TERMI/TIME)
                DDOWN = DDOWN+SI
c             WRITE(OUT,1055)TIME,DISTI(L),SI
c1055         FORMAT(' TIME =',F6.1,' DISTI =',F6.1,' SI =',F5.2)
15           CONTINUE
             WRITE(FILE,1060)TIME,SW,SI,DDOWN
1060         FORMAT(F10.2,18X,F6.3,26X,F6.3,30X,F6.3)
             X(I) = TIME
             Y(I) = DDOWN
20        CONTINUE
C
30        CONTINUE
C
C
C         CREATE OUTPUT FILE FOR PLOTTING
C
45        IPLOT = 9
          OPEN(UNIT=IPLOT,NAME='STRIP.PLO',TYPE='NEW')
          K = 1
          IJ = I-1
          J = IJ/10
          DO 2000 II=1,J
              WRITE(IPLOT,3000) (X(I1),I1=K,K+9)
              K = II*10+1
 2000     CONTINUE
          IF(J*10.EQ.IJ) GOTO 2010
          WRITE(IPLOT,3000) (X(I1),I1=K,IJ)
 2010     CONTINUE
          K = 1
          DO 2020 II=1,J
              WRITE(IPLOT,3010) (Y(I1),I1=K,K+9)
              K = II*10+1
 2020     CONTINUE
          IF(J*10.EQ.IJ) GOTO 2030
          WRITE(IPLOT,3010) (Y(I1),I1=K,IJ)
 2030     CONTINUE


 3000     FORMAT(<10>(F8.1))
 3010     FORMAT(<10>(F7.3))
 C
          CLOSE(UNIT=IPLOT,DISPOSE='SAVE')



 9998     FORMAT(I8)
 9999     FORMAT(I4)
 C
 C
          CLOSE(UNIT=FILE,DISPOSE='SAVE')
          END
```

APPENDIX SIX

ENVIRONMENTAL ISOTOPE THEORY

APPENDIX SIX

ENVIRONMENTAL ISOTOPE THEORY

A6.1 INTRODUCTION

The term environmental isotope refers to those isotopes which are globally distributed in varying concentration in the environment. The two isotopes used in this study are oxygen-18 (^{18}O) and tritium ($T = {}^{3}H$). Both these isotopes occur naturally, but tritium concentrations increased sharply following atmospheric bomb testing in the 1950s and 1960s.

Oxygen-18 and triyium are valuable water tracers because they are naturally occurring constituent atoms of water molecules.

A6.2 OXYGEN-18 IN HYDROLOGY

Oxygen-18 concentrations are given in δ values (in parts per thousand, $^{0}/_{00}$) where

$$\delta(^{0}/_{00}) = \left(\frac{R_{sample}}{R_{v-smow}} - 1\right) \times 1000$$

and R is the $^{18}O/^{16}O$ ratio. V-SMOW is the Standard Mean Ocean Water held at IAEA, Vienna. Measurement error is +/- 0.15% for $\delta^{18}O$ (95% confident level). Oxygen-18 was selected for this study as the level of accuracy is higher than that gained for deuterium. Where changes in isotopic ratio are expected to be small, clearly the greater accuracy will enhance any conclusions arrived at in the course of a study. Deuterium sampling accuracies are only +/-1.0% (95% confident level).

Natural water consists of approximately 99.8% $H_2{}^{16}O$ (molecular weight = 18), ^{16}O being the common isotope of oxygen, and 0.2% $H_2{}^{18}O$ (molecular weight = 20), ^{18}O being the heavy rare isotope of oxygen.

The δ values of any atmospheric vapour or non-oceanic water are the end result of successive processes of evaporation, condensation, mixing and occasionally, isotopic exchange with chemical forms other than chemically free water. Most of these processes involve some degree of isotope separation (fractionation).

The heavy molecule $H_2{}^{18}O$ occupies the condensed phase preferentially and hence oceanic vapour is strongly depleted in ^{18}O relative to the ocean surface. As water vapour rises and cools some condensation can occur leading to precipitation. As condensation and precipitation occur, the vapour becomes increasingly depleted in ^{18}O. The general trend is, therefore, towards a lower concentration (more Negative values) of ^{18}O as temperature decreases.

Oxygen-18 values in precipitation will as a consequence vary with:

a) season, with more negative δ values in winter.

b) altitude, with more negative δ values at higher altitudes.

c) mean temperature change, with more negative δ values during colder periods at a specific location.

Groundwater tends to take on the 'isotopic signature' that reflects the mean isotopic composition of the recharge area. This has important implications regarding the sourcing of groundwaters. In this study it has been shown that both spring, alluvial and thermal waters are all of local meteoric origin. Preciitation derived groundwater shows oxygen-18 isotope ratios that lie close to a line known as the Meteoric Water Line.

A6.3 TRITIUM IN HYDROLOGY

Tritium concentrations are reported as Tritium Ratios (TR) where 1TR represents a T/H ratio of 10^{-18}.

Each groundwater reservoir is characterised by water quantity, inputs and outputs, internal structure, and dynamic characteristics. Tritium enters a reservoir by one or more inputs, whose rate of water inputs and tritium concentrations vary with time. The internal reservoir processes (advection, dispersion and other mixing processes, possible chemical exchange) produce a tritium distribution which varies with location and time. One approach used to examine reservoir characteristics is to establish likely reservoir models and to determine which of these are consistant with both tritium distribution and other information.

A6.3.1 Tritium Input to Hydrological Systems

In the case of most freshwater systems, the chain of tritium input starts with the fall of precipitation. Two mechanisms of groundwate rechare in New Zealand are by infiltration from major rivers into gravel aquifers and by direct infiltration of precipitation. Within New Zealands volcanic regions (including Banks Peninsula) the volcanic rock aquifers are predominantly recharged by direct infiltration of precipitation. Most rivers and streams in such areas are fed from groundwater and the ready response of streams to precipitation is often a pressure response, with older water being displaced to springs and streams in response to a remote input of river water at the top of the reservoir. Tritium concentrations have shown that the release of water from volcanic rock to springs and streams often takes several decades or longer; this is a very importent finding for catchment management policy, particularly in terms of water supply potential and long-term effects of pollution in the catchment areas. If the evidence of such long drainage times is combined with flow measurements, an estimate is obtained of the quantity of water in the reservoir feeding the discharge.

A6.3.2 <u>Age Spectra</u>

Mixing of the inputs inside water reservoirs produces an age spectrum of the water at any location. Age in this sense means the time since any water component entered the reservoir.

Usually hydrological problems involve deducing an age spectrum, or at least the mean residence time, from one or more measured tritium reponses. The most commonly considered theoretical concept is the exponential age distribution. This simple distribution applies in the case of a well-mixed box with balanced input and output of water; the ocean mixed layer and many large lakes approximate very closely to this concept. When this distribution applies, present measurements may not yield a definite indication of residence time as following 1970 the responses of this system begin to run together and are not well defined (see Fig 4.9).

Figure 4.10 shows an analysis for the other highly idealised 'piston-flow' situation in which water flows through the aquifer as through a pipe, without significant dispersion in the flow disection. In this case highest concentration presently exist for flow times of around 20 years.

Analyses of the two tritium measurments gained for the High Altitude study indicates that a combination of the above two models adequately approximates the age distribution of spring X1a groundwater, ie and exponential-piston flow model, with the exponential reservoir volume three times that of the piston-flow volume.

Tritium measurements taken from the Sulphur Spring (Purau Valley), Well 13 (Purau Motor Camp) and the Deep Well (Orton Bradley Valley) all show very low values indicating no input of thermonuclear Tritium and therefore a deduced mean minimum age for these waters is 50 years (Table A6.1).

Sample Location	Date	TR	$\delta^{18}O$
Sulphur Spring, Purau Valley N36 GR 902295	3/88	-0.03	-7.91
Well 13, Purau Valley M36 GR 899296	3/88	0.11	—
High Altitude Spring X1a N36 GR 907239	3/88 10/88	4.27 4.05	-7.66 – -7.85
High Altitude Spring N36 GR 900239		—	-7.58

Table A6.1 Isotope Data

APPENDIX SEVEN

COMPARISON WITH OVERSEAS EXAMPLES

A7.1 The Hawaiian Islands

A7.2 Groundwater of the Chyulu Region, Kenya

APPENDIX SEVEN

A7.1 THE HAWAIIAN ISLANDS

A7.1.1 Precipitation and Runoff

The average annual rainfall of the Hawaiian islands ranges from less than 875mm to over 2500mm, compared to averages of 650 to 1300mm for Banks Peninsula. The most important source of precipitation results from orographic ascent over the volcanic mountains by northeasterly trade winds, which prevail about 90 percent of the time in summer and about 50 percent of the time in winter (Peterson, 1972). Rainfall is more strongly seasonal in the drier areas than the wetter ones due to the orographic effect of the tradewinds. Areas that face the tradewinds tend to be wetter than the leeward areas (Fig. A7.1).

Hawaiian streams are in general short and steep and runoff depends largely on the intensity and duration of rainfall. Most of Hawaii's drainage basins are very small, the average being 2.59 km^2 and most being less than $13km^2$ (Peterson, 1972). Most watersheds are characterised by steep slopes and steep valley walls with little channel storage. Flood hydrographs as a result tend to be characterised by a very sharp rise and recession. The time to peak flow is usually only a few hours at most (Fig. A7.2).

Owing to the highly permeable nature of the volcanic rocks and soils in the area infiltration rates may exceed 6.9×10^{-1} mm/sec. in some areas. Some of the younger volcanic rocks (ie lavas that have erupted within the last 100 years) are so permeable no runoff occurs at all. Usually intense storms produce high runoff, while moderate storms show relatively small amounts of runoff.

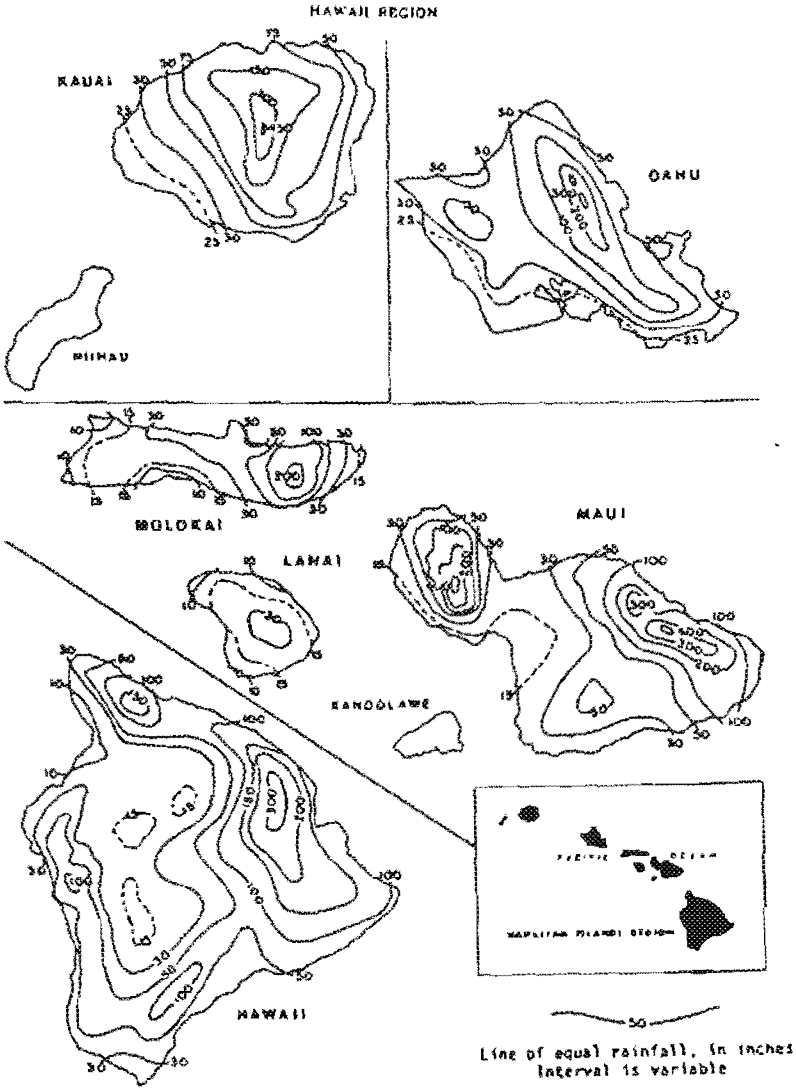


Fig. A7.1 Map of the Hawaiian Islands showing lines of equal annual rainfall in inches. (From Takasaki, 1978)

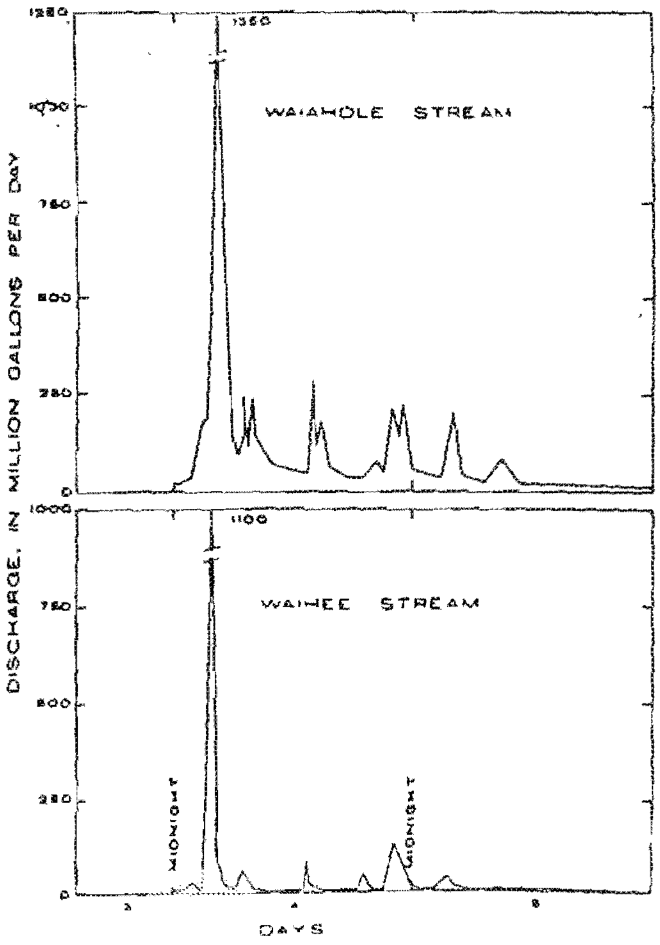


Fig. A7.2 Hydrograph showing discharge in Waihee Stream and in Waiahole Stream, during the period February 3-5 1965. (From petersen, 1972)

In many areas evapotranspiration rates often approach the evaporation rate from a free water surface. The average pan evaporation differs widely from place to place, but on the larger islands ranges from 500mm to 200mm (Takasaki, 1978).

A7.1.2 Groundwater

Most groundwater is stored in reservoirs ranging up to 300m or more below sea level. The principal fresh groundwater reservoirs consist of accumulations of thin basaltic lava flows. These reservoirs contain interconnected water bodies divided into groundwater 'compartments' by dikes in the interior of the islands, or that are in dynamic equilibrium with the underlying saline groundwater in the outer rims of the islands - referred to as "dike-impounded" and "basal" water respectively (Fig. A7.3). Other water bodies, small in comparison, are perched above and sometimes isolated from these interconnected water bodies (Peterson, 1978).

Geological features of the Hawaiian Islands 'type area' account for the vast potential to store groundwater. Most lavas of the Hawaiian islands are less than three to five million years in age, the flows range in thickness from centimetres to a hundred metres or more, but most are less than six metres. This is an important feature as most of the water bearing structures in lavas are associated with the surface or near surface portions of flows. Strearns and Macdonald (1946) note that permeability usually decreases as the lava flow increases in thickness. They also rank the following features in terms of their importance as water bearing structures: (1) interstitial spaces in basal breccias, (2) cavities between beds, (3) joints, (4) lava tubes, (5) gas vesicles, (6) fissures produced by faulting and cracking after the lava has cooled, and (7) tree-mould holes. The horizontal component of permeability exceeds the vertical in most cases.

The principal source of fresh water on the islands is the lens shaped basal fresh water body which displaces denser sea water. This writer believes that there is no evidence for the existence of such a water body underlying Banks Peninsula, and therefore the two other types of groundwater found in Hawaii are more applicable to the Banks Peninsula situation.

Perched aquifers exist where rocks that are relatively impermeable underlie those that are permeable. Perching layers include (in order of importance as suggested by Stearns and Macdonald, (1946)) intrusive rocks, ash beds, dense lava flows, soil and alluvium. Although their areal extent is often limited, hence small volumes of storage, this source of water has been valuable because their high altitude makes pumping unnecessary and salt water intrusion impossible. Most perched aquifers are identified by the existence of springs. This is also true of Banks Peninsula where most high altitude groundwater flows from aquifers perched over relatively impermeable layers such as ash beds.

Dike - impounded groundwater bodies, like perched water bodies, are usually identified by natural spring discharges. Large volumes of groundwater are stored in dike bounded compartments to hundreds of metres above sea level. These provide a stable source of groundwater on the Hawaiian islands. Some writers have suggested the existence of groundwater compartments on Banks Peninsula (eg Sanders, (1986), Namjou, (1988)), and while dike complexes exist in both the Lyttelton and Akaroa volcanics, no real evidence has been found to support this view.

A7.2 GROUNDWATER OF THE CHYULU REGION, KENYA

Between Nairobi and Mombasa the Chyulu Range exists as an 80 x 6km wide belt of cinder cones. This belt is flanked by basaltic lava fields for 8km on either side. The Chyulu structure can be regarded as a basaltic shield volcano with strong cinder cone development. The fresh nature of lavas and fossil evidence suggests an Upper Pleistocene age for the Chyulu volcanics (Fig. A7.4).

Average annual rainfall is 1375mm or less, similar to parts of Banks Peninsula. There is no surface drainage on either the cone belt or lava field, but infiltrated rainwater emerges at a number of springs situated at the periphery of the lava field. The lava field overlies a relatively impermeable basement, while the high permeability of the lavas is governed by the presence of high void space in pyroclastic deposits, jointed lavas, scoriaceous lava surfaces and the narrowness of individual flows. Regional groundwater flow is to the south east on account of the inclined basement surface. Jointed pahoehoe flows are the main aquifers, but water also moves through local limestone fissures in paludinal beds where present.

Temperley (1960) found that pahoehoe lavas made better aquifers compared to aa flows. Aa flows usually were single units of great thickness and could only conduct water on their blocky or scoriaceous surfaces and flanking parts.

Temperley postulates that from the alignment of the vents in chains it is probable that dike swarms exist to confine groundwater at high altitudes. The occasional spring is to be found at high altitude, but most are found on the flanking lava field. The location of Banks Peninsula springs, on the whole, cannot be explained by the presence of dikes, and studies reveal that it is the presence of perching layers such as ash beds that control spring distribution. The lack of seasonal variation of some of these springs is explained by slow leakage from one pen to the next. A simple water balance suggests that 9 per cent infiltration of rainfall is needed to maintain current spring outflow from the area compared to less than 5% for springs in the Purau and Kaituna Valleys of Banks Peninsula. Temperly also suggests that water can travel up to 48 km from the point of infiltration until discharge occurs at the surface via springs.

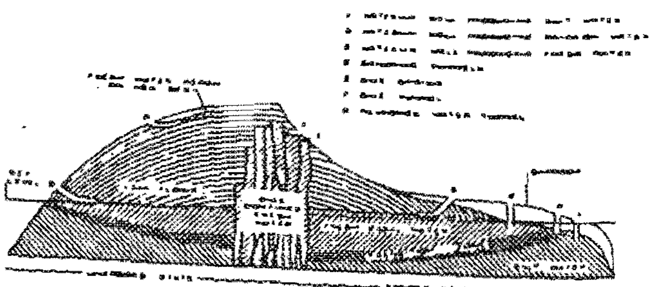


Fig. A7.3 Cross section of typical volcanic dome showing occurrence and recovery of ground water
(From Petersen, 1972)

KEY TO Fig A7.4
(opposite)

- Alluvium.
- Basaltic lava.
- Sandy soil over Basement gneisses and schists (except in SW where Basement is covered by volcanic rocks, lahar deposits and alluvium from Kilimanjaro).
- Fissures inferred from alignment of vents.
- Geological boundaries.
- Edge of Chyulu lava field.
- Edge of Mbioni Lava.
- Edge of areas of alluvium and swamps.
- Streams, permanent.
- Streams, seasonal or storm watercourses.
- Two inferred, permanent sub-lava watercourses, SW of Kibwezi.
- Watershed on Basement country.
- Inferred watershed on Basement concealed below volcanic rocks.
- Outline of Basement inselberg with crest line where acute.
- Diagrammatic formlines on basal slope of Kilimanjaro.
- Altitude in feet (approx.).
- Swamp.
- Springs.
- Discharge of spring or flow of river in cusecs.
- Raingauge.
- Borehole.
- Well.
- Road.
- Motorable track.

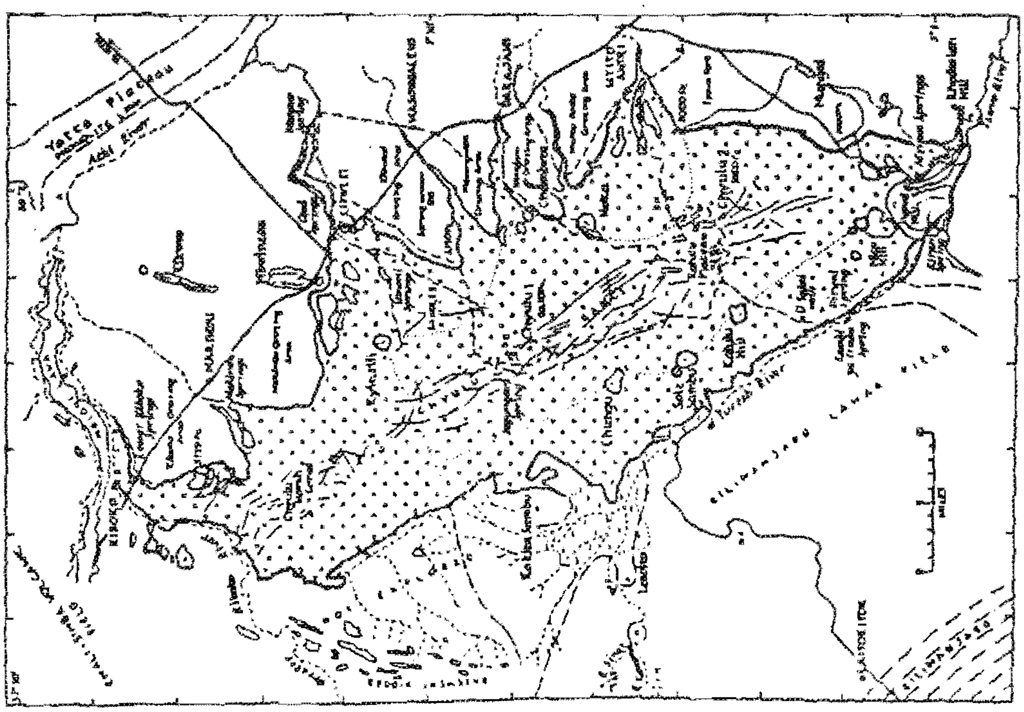


Fig A7.4 Map of the Chyulu Volcano area. A freehand reduction and simplification of the regional map.

APPENDIX EIGHT

PETROGRAPHIC AND MINERALOGICAL SUMMARY OF VOLCANIC FORMATIONS FOUND IN DIAMOND HARBOUR

A8.1 Introduction

A8.2 Lyttelton Volcanics

A8.3 Mt Herbert Volcanics

A8.4 Church and Stoddart Volcanics

APPENDIX EIGHT

A8.1 INTRODUCTION

A brief summary of petrographic and mineralogical information relevant to those volcanic rocks found in Diamond Harbour is considered necessary in order to understand the groundwater chemistry of the Diamond Harbour region. The following summary is based on Sewell (1985).

Plagioclase feldspar composition represents a solid solution series from albite ($Na[AlSl_3O_8]$), (Ab), to Anorthite ($Ca[AiSl_3O_8]$), (An). The division of the particular plagioclase mineral follows the standard format. For example, a composition of An_{70} describes the proportion of An in this case 70%, to Ab in this case the remainder, 30%.

Olivine composition represents a solid solution series from forsterite Mg_2SiO_4 (Fo) to fayalite Fe_2SO_4 (Fa). Composition of olivines is presented in relation to the proportions of each end member present. For example, an olivine composition of Fo_{80} represents a composition of 80% Fo to 20% Fa.

A8.2 LYTTELTON VOLCANICS

Lyttelton lava flows are mainly composed of grey black, moderately weathered, porphyritic hawaiite and mugearite. In most lavas plagioclase (An_{70} - An_{25}) phenocrysts dominate with subordinate olivine (Fo_{80} - Fo_{40}) and titanoferous augite. Ther groundmass is rich in plagioclase, olivine, pale green augite and titanomagnetite.

Trachyte lavas and dikes have feldspar compositions ranging from alkalai feldspar to andesine and augite is a common accessory mineral in the groundmass.

A8.3 MT HERBERT VOLCANICS

Porphyritic Orton Bradley Hawaiites have olivine as the dominant phenocryst phase with subordinate plagioclase and clinopyroxene. The main groundmass constituents are plagioclase, clinopyroxene. olivine and Fe-oxide.

Average composition of olivine phenocrysts in Orton Bradley Hawaiite lavas is Fo_{70} and the groundmass Fo_{60}. Plagioclase feldspars are labradorite in phenocryst and groundmass phases. Titano-magnetite is the main Fe-oxide.

The porphyritic lavas of the Mt Herbert Hawaiite Formation have olivine as the dominant phenocryst mineral with subordinate clinopyroxene and plagioclase. The groundmass is rich in olivine, clinopyroxene and Fe-oxide.

The Mt Herbert Hawaiite olivines average Fo_{70} with groundmass olivines slightly less at FO_{57}. Labradorite plagioclase feldspar is also found in these lavas.

A8.4 CHURCH AND STODDART VOLCANICS

Olivine (Fo_{84} - Fo_{72}) is the dominant phenocryst phase in the Church Bay Olivine basalts, with subordinate clinopyroxene and rare plagioclase. Groundmass constituents are plagioclase (labradorite), clinopyrene, olivine (Fo_{69}) and Fe-oxide (titanomagnetite).

Stoddart Point Olivine-Basalts consist of fine-grained, fresh to moderately weathered, basanites, alkalai-basalts and olivine hawaiites. If present, phenocrysts are usually olivine (Fo_{86} - Fo_{58}), or sometimes clinopyroxene (Ca-rich diopside). The groundmass consists of plagioclase (labradorite, An_{60} - An_{50}), clinopyroxene, olivine and Fe-oxide (titanomagnetite).

APPENDIX NINE

WATER BALANCE CALCULATIONS

A9.1 Water Balance Calculations for the Purau Valley

A9.2 Water Balance Calculations for the Upper Purau Valley

APPENDIX NINE

A9.1 WATER BALANCE CALCULATIONS FOR THE PURAU VALLEY

A summary table of water balance calculations for the Purau Valley is presented in Table 3.5. The procedure and assumptions that these calculations are based on are as follows:

A9.1.1 Data Sources

a) Rainfall totals were calculated for each rainfall event using the isohytal technique. The resulting figures represent an equivalent rainfall total, expressed in millimetres over the total catchment area of approximately 17 km^2 for the Purau Valley.

b) Purau River flow totals for the period 22/1/88 to 4/8/88 were calculated from the river hydrograph created for this river (Figs. A9.1 and A9.2). River flow totals were calculated for weekly periods and are expressed in millimetres over the catchment area. If a major river fresh coincided with the end of a weekly period, the period was extended until river flow had returned to normal baseflow levels.

c) Quickflows were separated from hydrographs drawn for the individual storm events occurring over the balance period. NCCB computer programmes were used to calculate quickflow components which are also expressed as millimetres over the total catchment area (Fig. A9.3).

d) Potential Evapotranspiration (PET) figures from Christchurch Airport were used for the period 22/1/88 to 28/4/88 (Table A9.1). For the remaining period 28/4/88 to 4/8/88 weekly PET figures for the Ashley State Forest were used because the Meteorology Service only calculated PET data for the period of September to April of the following year. While it would have been ideal to use locally derived

E.T. 1987/88 Season

CHRISTCHURCH	I. Jan. 1988	II. Feb.	III. Mar.	IV. Apr.	V. May.
1	3.8	4.8	3.6	MIS	
2	4.9	0.6	3.1	1.9	
3	5.0	1.2	3.3	1.2	
4	5.0	2.1	4.1	1.3	
5	2.7	2.8	3.4	2.0	
6	4.9	4.0	3.4	2.4	
7	3.5	2.0	1.1	1.0	
8	5.1	1.9	1.8	0.9	
9	2.6	2.3	1.3	1.2	
10	4.1	2.7	0.7	1.0	
11	3.0	3.2	2.5	1.3	
12	4.9	3.4	3.0	1.8	
13	3.3	1.4	1.9	1.6	
14	2.6	1.0	2.5	1.9	
15	4.6	1.5	1.7	1.7	
16	4.8	1.8	2.5	2.0	
17	2.9	2.4	2.7	0.7	
18	2.6	2.4	1.5	1.4	
19	1.1	3.5	1.9	1.6	
20	[illegible]	2.1	0.8	0.4	
21	3.8	2.0	2.6	1.4	
22	4.2	2.8	1.9	1.5	
23	5.0	3.7	2.5	1.6	
24	5.1	3.9	2.7	mis	
25	5.0	----	2.2	1.5	
26	4.8	2.8	1.5	1.5	
27	3.0	4.0	0.9	1.2	
28	1.9	----	1.1	0.7	
29	3.4	----	1.6	0.5	
30	4.9	----	2.2	1.3	
31	4.6	----	1.9	----	
MONTHLY TOTALS:					
E.T	121.3	66.3	67.9	39.5	
RAINFALL	17.4	40.6	21.7	16.9	

Table A9.1 Potential Evapotranspiration Figures for Christchurch Airport over the period Jan. to April 1988.

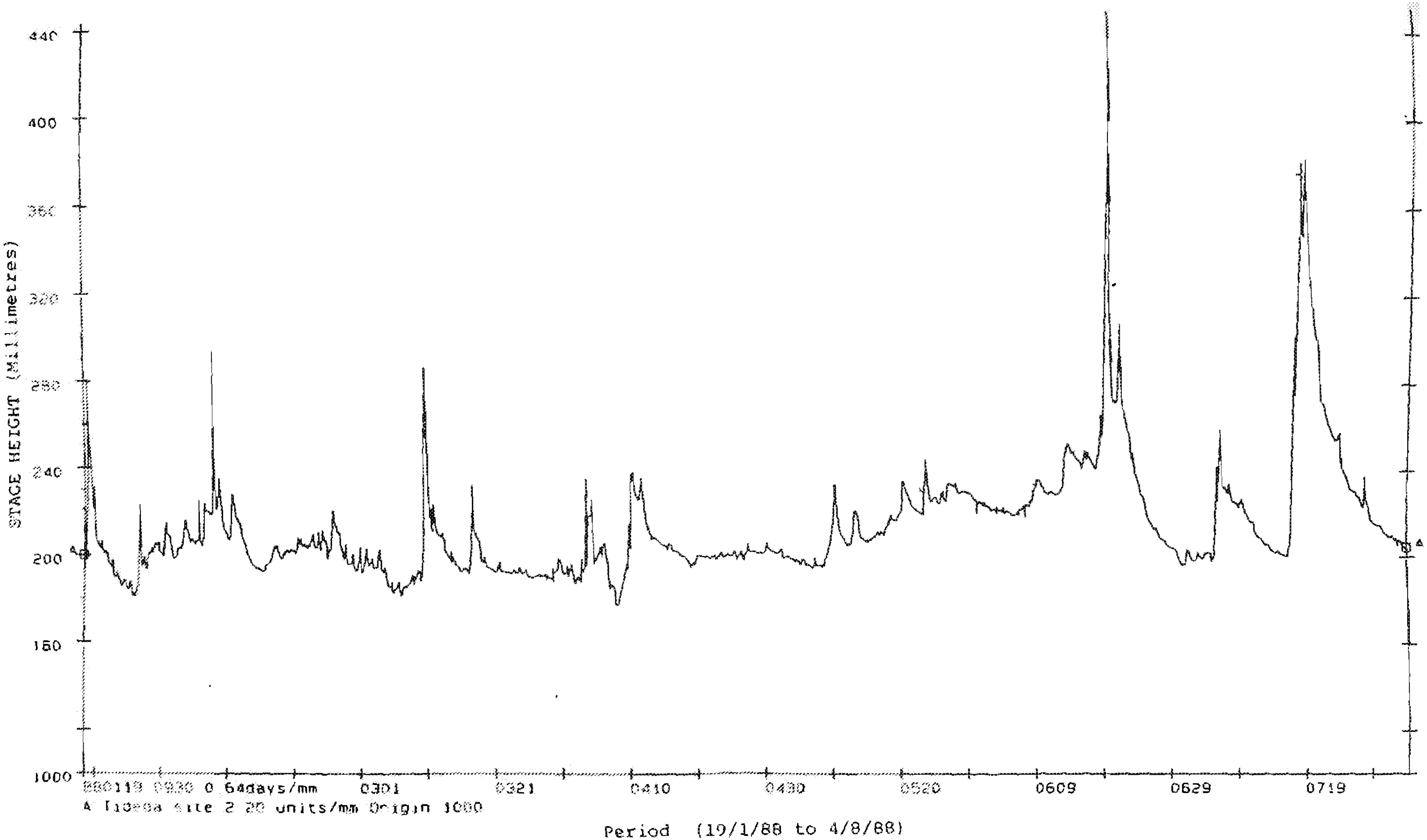


Fig. A9.1 STAGE RECORD for the PURAU VALLEY

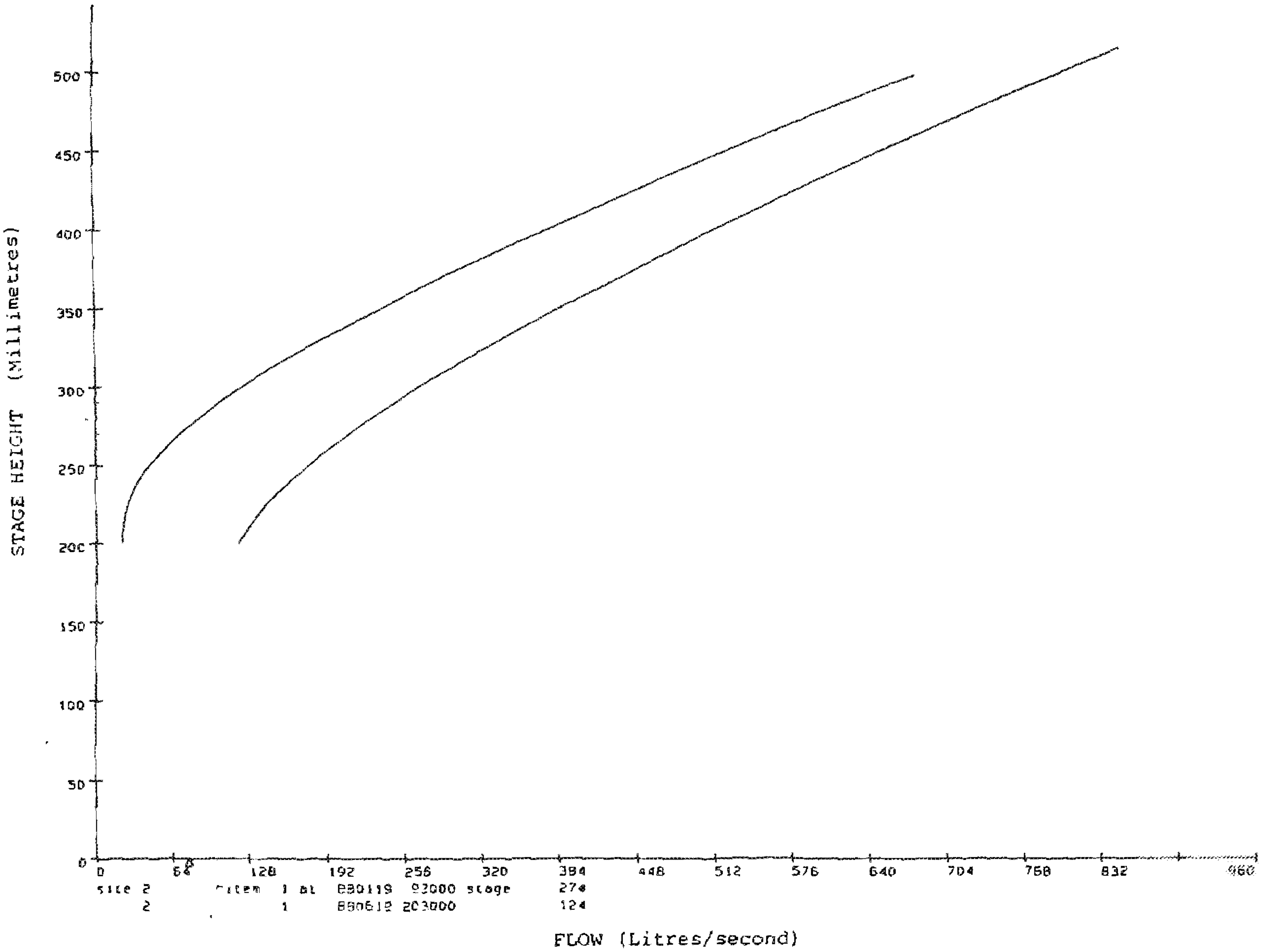


Fig. A9.2 RATING CURVES FOR THE PURAU RIVER

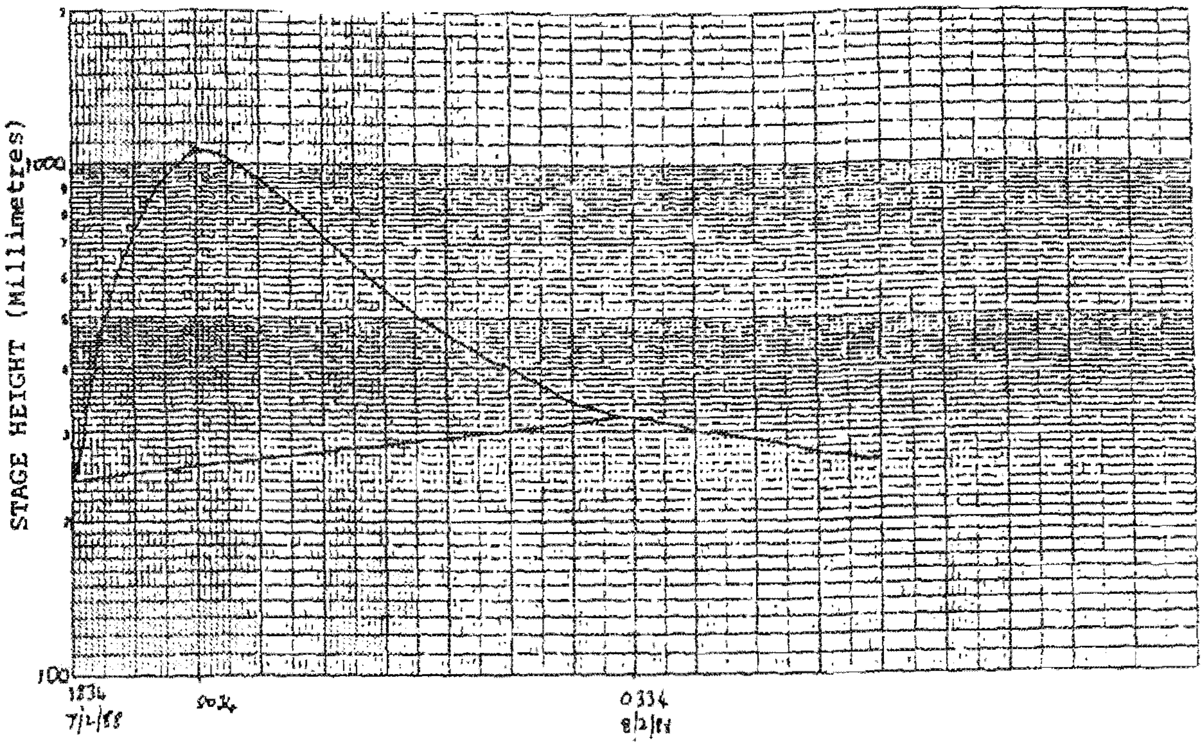


Fig. A9.3 Example of a separated hydrograph for the event 7/2/88 to 8/2/88.

PET figures, a reasonable level of accuracy is still possible using figures derived for the Canterbury Plains (R. Jackson, pers. com.).

A9.1.2 Calculation of Actual Evapotranspiration and Soil Moisture Deficit

Figure A9.4 represents a technique used by Forestry Research Institute (FRI) soil physicists to calculate actual evapotranspiration (AET) figures and the soil moisture deficit for a given catchment. Calculations are based on what is considered to be an average water holding capacity of the soils represented in the Purau Catchment. The average depth of regolith in the Purau Catchment is considered to be about 1.3m. From Table 4.1 the average water holding capacity of the Purau Valley soils is considered to be about 150mm.

Experiments by FRI soil physicists have shown that when a soil is at field capacity, actual evapotranspiration will proceed at the potential rate until soil moisture levels reach 50% of their total holding capacity. In the Purau Valley this means that until soil moisture levels are reduced to 75mm (ie 50% of 150mm) the ratio of AET/PET will be one (Fig. A9.4). As soil moisture levels are reduced below 75mm the ratio of AET/PET falls below one. To calculate weekly AET figures, the ratio of AET/PET for the current soul moisture state, is multiplied by the calculated PET figure.

A starting point of -75mm for the soil moisture state at 22/1/88 appears under the soil moisture (sm) column in Table 3.5. Studies by FRI scientists indicate that at Ashley Forest soil moisture levels had been reduced to 50% of their maximum at22/1/88, hence 50% of 150mm is 75mm.

Positive figures indicate a soil moisture surplus existed while negative figures indicate a soil moisture deficit situation.

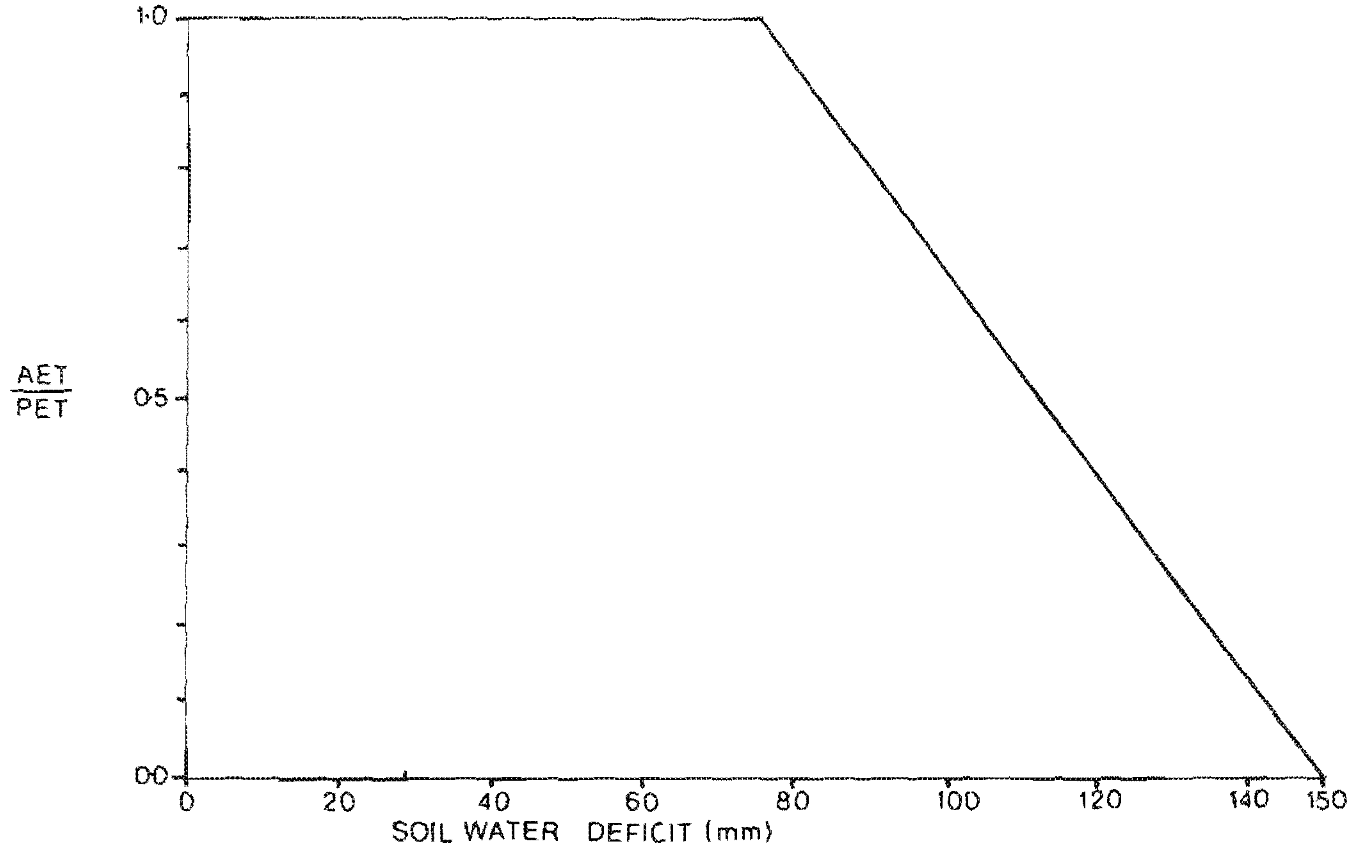


Fig. A9.4 Graph to calculate actual evapotranspiration rate from calculated Potential evapotranspiration figures.

Table 3.5 shows that for the whole of Purau Valley for the period 22/1/88 to 14/7/88 a deficit situation existed in the soil. At the end of the balance period (4/8/88) a soil moisture surplus of about +12mm existed in the Purau Catchment.

A9.2 WATER BALANCE CALCULATIONS FOR THE UPPER PURAU VALLEY

Similar water balance calculations were made for the upper Purau Valley over the period 10/8/88 to 8/9/88 (Table 4.6). The starting figure of +15.88 for the soil moisture situation at 10/8/88 was found by continuing the balance calculations for the whole Purau Valley which are presented in Table 3.5. Actual evapotranspiration figures used were averages calculated over several years for the months of August and September, at the Ashley State Forest.

Table 4.6 shows that a soil moisture surplus existed throughout the balance period, and was calculated to be about 89mm on the 8/9/88.

APPENDIX TEN

PIEZOMETRIC CONTOUR ANALYSIS

A10.1 Piezometric Analysis

A10.2 Well Level Monitoring

APPENDIX TEN

A10.1 PIEZOMETRIC ANALYSIS

Using the average winter (June/July 1988) and summer (January/February 1988) well levels for wells 8, 12 and 13, piezometric contours were drawn for the Lower Purau Aquifer. None of the wells used in this study have been surveyed and therefore piezometric contours represent approximate values only. Flow through any vertical section of aquifer,

$Q = TIw$ where w is the width of aquifer being considered, Q is the aquifer flow in m^3/day, T is the aquifer transmissivity and I is the hydraulic gradient.

If the assummed width of the buried river channel is 64m, and T has been calculated at 11.92 m^2/day, and the hydraulic gradient, $I = h_1 - h_2/L$ where, $h_1 - h_2$ is the difference in hydraulic head between any two points along the flow path, and L is the length of flow path,

then $Q = 11.91 \times 0.01 \times 64$
$= 7.6$ m^3/day for the Lower Purau Aquifer

Date \ Well No.	1	2	3	4	5	6	7	8	9	10	12	13
20/10/87	87	19	75	101	100	165	87	39	73	65	200	-
9/11/87	94	54	-	176	121	208	117	-	120	106	222	298
24/11/87	96	69	-	201	140	231	134	-	140	143	228	365
9/12/87	120	86	120	129	138	243	137	157	152	145	222	237
13/1/88	153	107	144	154	163	273	164	153	186	176	244	263
4/2/88	161	163	147	156	169	199	169	151	194	192	241	333
29/2/88	-	169	151	160	175	179	177	169	202	193	323	404
14/3/88	-	165	152	162	177	249	178	171	204	196	249	295
30/3/88	-	163	151	161	178	272	179	173	206	197	242	263
14/4/88	-	162	149	162	176	279	175	170	203	193	244	292
29/4/88	-	163	-	163	175	283	172	173	197	195	236	270
12/5/88	-	161	136	-	168	282	163	159	190	185	203	251
31/5/88	-	158	134	149	162	246	157	158	183	174	226	213
13/6/88	-	158	-	146	158	246	153	147	179	177	227	214
21/6/88	-	152	119	135	150	245	143	140	172	-	223	-
22/6/88	-	-	-	138	150	243	143	139	-	-	222	194
14/7/88	-	151	120	134	144	232	138	135	165	222	156	199
25/7/88	-	149	108	122	132	155	123	113	145	-	226	199

Table A10.1 Piezometric Well Record (water levels in cm below the well head)

APPENDIX ELEVEN

SPRING EXPERIMENT DATA

A11.1 Calculations of reservoir size

A11.2 The MK4B Automatic Liquid Sampler

A11.3 Continuous Flow Measurements for Spring X1a

A11.4 Daily Record of Spring X1a flow and springs X1 to X18 flow

A11.5 Rating Curve For Spring X1a

A11.6 Diamond Harbour Annual Spring Records

A11.7 Specifications for the mini V-notch Weir used in Spring Experiment

APPENDIX ELEVEN

A11.1 CALCULATIONS OF RESERVOIR SIZE

A11.1.1 Total Rock Volume (Upper Purau Valley)

The total volume of rock above the 760m contour, from which springs X1 to X18 exist was calculated as follows:

1) Four cross sections through the area on a 1:10,000 scale plan of the area were drawn, and the areas of each cross section in m^2, were calculated. The average cross sectional area was then calculated at $49{,}881m^2$.

2) The distance between the first and last springs in this area was calculated at approximately 1,000m.

3) The total rock volume was therefore calculated as $49{,}881 \times 1{,}000 = 49{,}881{,}000m^3$.

A11.1.2 Calculation of Total Reservoir Size for Springs X1 to X18

Total reservoir size for the area was calculated as follows:

1) A total median flow for springs X1 to X18 over the period of June 1987 to June 1988 was calculated at $295m^3$/day.

2) Tritium measurements indicate that spring X1a groundwaters have a mean residence time of 10 to 25 years. The assumption is made that springs X1 to X18 all have approximate mean residence times of 10 to 25 years.

3) Knowing a mean residence time of the groundwaters and a median flow then,

- a residence time of 10 years at 295m^3/day gives a reservoir of 1,073,800m^3 in volume.

- a residence time of 25 years at 295m^3/day gives a reservoir of 2,684,500m^3 in volume.

1,073,800m^3 represents 2% of the total rock volume calculated above, and 2,684,500m^3 represents 5% of the total rock volume. Therefore, it is reasonable to assume that the total reservoir that exists for springs X1 to X18 is approximately 2 to 5% of the total rock volume.

A11.1.3 Calculation of the Reservoir Size for Spring X1a

Calculation of the reservoir size of spring X1a alone is similar to the calculations made for the total reservoir volume.

1) Assume a median flow of 10.6m^3/day over the period of 26/7/88 to 16/9/88, and this is typical of the springs annual flow regime.

2) Assume that the mean average residence time of this spring water is between 10 and 25 years.

3) Then, the reservoir for spring X1a alone must be between 38,787m^3 and 96,969m^3. This represents between 1.4 and 3.6% of the total calculated reservoir size.

A11.2 THE MK4B AUTOMATIC LIQUID SAMPLER

The MK4B Automatic Liquid Sampler was used in conjuction with the EC 2001 Electronic Control System to collect water samples for the High Altitude Spring experiment. The MK4B Sampler consists of 24 bottles connected to an actuator which is controlled by a battery operated electronic control system.

To set the system up for use, a vacuum pump is used to vacuum out the 24 bottles. The catches that close off each bottle are set and the hose assembly is attached (Fig. A11.1). The filter end of the hose is placed in the 44-gallon drum. The actuator is now at the zero location ready to begin sampling from bottle one to bottle 24 at the pre-determined time setting. In this case initially sampling was at four hourly intervals (using two samples each set to sample eight hourly, but one offset from the other by four hours). This proved unnecessary so one sampler was used set to sample eight hourly. The battery operated electronic control system can be set to any time delay needed. The process was initiated by the first sample being manually tripped on each visit, thus 24 bottles sampling eight hourly meant the site was visited every seven or eight days.

On each visit bottles were emptied and placed in isotope sample bottles. The whole system was then reset.

A11.3 CONTINUOUS FLOW MEASUREMENTS FOR SPRING X1a

A Belfort water level recorder was used to record spring flow. The instrument is a chart operated instrument operating on a seven day cycle by a wind up clock. Zero flow was calibrated on the chart by stopping the spring flow into the 44-gallon drum. The position of the pen on the chart was noted for calibration. A rating curve for the V-notch wier used was available to convert stage readings into a flow record.

Each 7-day chart was digitised using a Forest Research Institute (FRI) digitiser into stage readings. These were converted into micro Tideda format so that the rating curve could be applied to give a flow record using the North Canterbury Catchment Board computer.

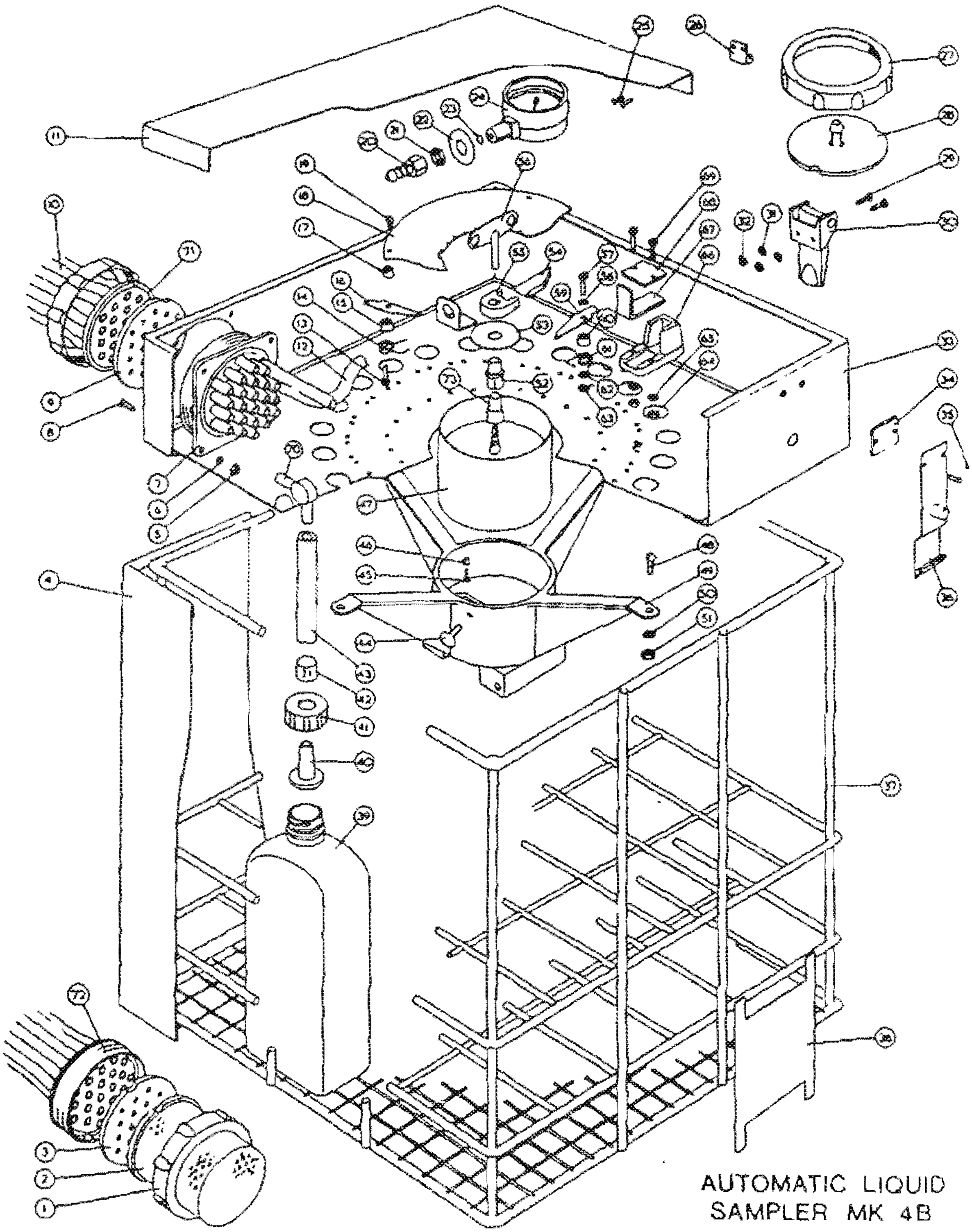
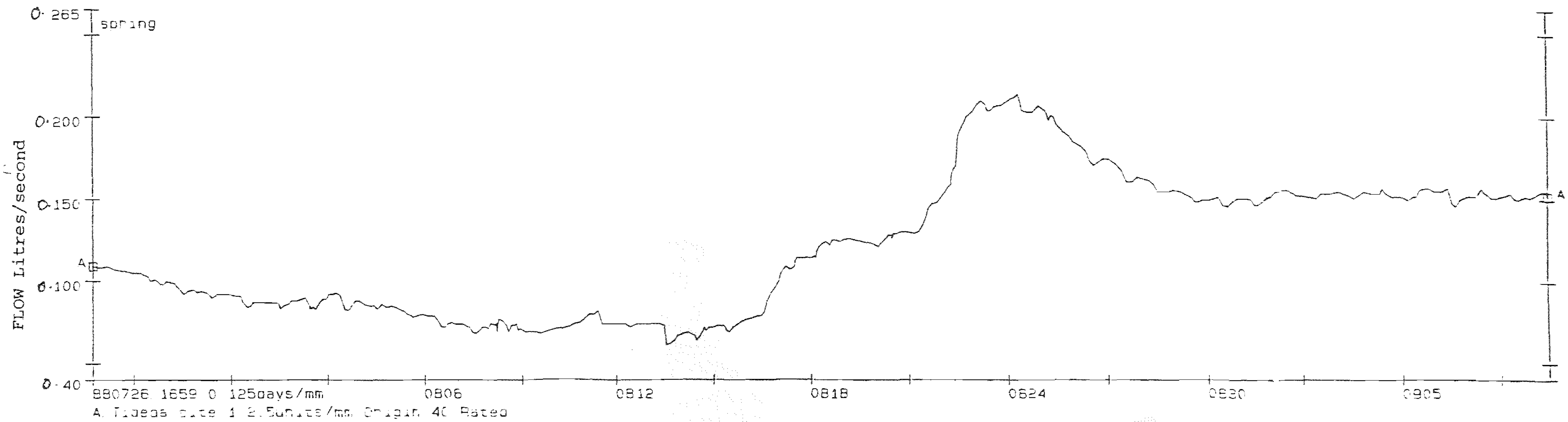


Fig. A11.1 THE MK4B AUTOMATIC LIQUID SAMPLER



SPRING X1a FLOW RECORD for the period 26/7/88 to 9/9/88

Date (1988)	Spring X1a Flow (l/min)	Springs X1-X18 Total Combined Flow (approx. only) (l/min)
27/7	6.5	342
28/7	6.1	320
29/7	5.8	301
30/7	5.5	288
31/7	5.3	276
1/8	5.2	270
2/8	5.3	279
3/8	5.3	276
4/8	5.1	267
5/8	4.9	254
6/8	4.6	238
7/8	4.3	225
8/8	4.4	228
9/8	4.1	216
10/8	4.4	228
11/8	4.6	240
12/8	5.6	293
13/8	5.3	279
14/8	4.1	216
15/8	4.4	228
16/8	5.1	267
17/8	6.7	349
18/8	7.3	383
19/8	7.4	389
20/8	7.7	405
21/8	8.3	436
22/8	10.8	564
23/8	12.4	649
24/8	12.4	649
25/8	11.8	614
26/8	10.6	596
27/8	10.0	555
28/8	9.5	524
29/8	9.1	496
30/8	8.9	477
31/8	9.0	480
1/9	9.2	502
2/9	9.2	499
3.9	9.2	502
4/9	9.2	502
5/9	9.2	502
6/9	9.1	496
7/9	9.2	499
8/9	9.2	496
9/9	9.1	496

<u>Average Daily Flows for Springs X1a and X1-X18</u>

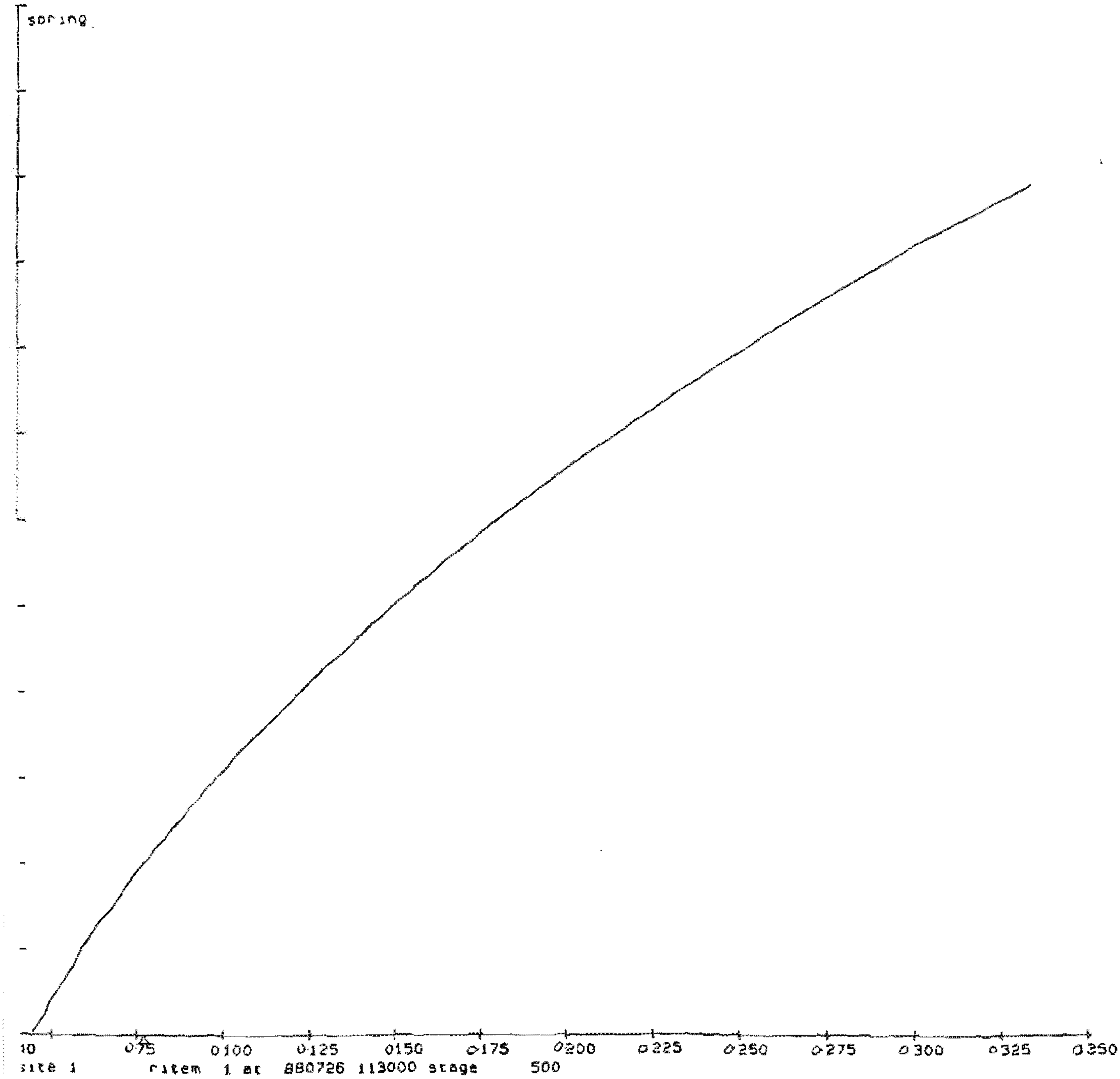


Fig. A11.5 Rating Curve for Spring X1a Flow Record

Spring Number	12/6/87	29/6/87	17/7/87	30/7/87	20/8/87	10/9/87
X1	51	108	173	88	36	61
X2	16	48	57	36	18	24
X3	6	30	51	24	6	12
X4	5	48	67	18	6	30
X5	5	12	18	12	6	9
X6	48	72	117	60	36	49
X7	13	24	33	18	12	24
X8	3	12	18	12	4	6
X9	3	4	12	3	2	2
X10	2	4	12	3	2	2
X11	2	4	12	3	2	2
X12	8	24	61	36	12	15
X13	10	18	43	24	12	12
X14	39	60	101	96	36	48
X15) X16)	4	42	80	36	18	24
X17	5	12	18	6	2	3
X18	2	8	18			2

Spring Number	25/9/87	19/10/87	29/10/87	26/11/87	17/12/87	18/1/88	22/2/88	15/3/88	31/3/88	18/4/88	5/5/88	30/5/88	28/6/88	26/7/88
X1	37	144	29	36	42	18	27	30	24	18	12	18	66	60
X2	21	48	24	18	18	9	15	12	12	9	6	9	24	24
X3	9	6	6		6	6	5	6	3	6	4	4	6	15
X4	12	66	21	6	6	2		5	4	3	1	1	18	12
X5	6	18	4	6	6	2	6	3	2	2	1	6	8	11
X6	37	84	48	24	48	24	48	36	30	24	15	24	39	48
X7	12	24	15	12	12	9	12	6	6	9	3	6	12	12
X8	3	24	1	3	2		2	2	2		1	6	4	6
X9	3	12	2	1	1						·		4	6
X10	1	6	1	1	1								1	12
X11	1	6	2	1	1	1		1				1	3	12
X12	12	36	12	6	12	2	6	6	3	3	1	3	12	12
X13	9	16	12	6	4	2	6	3	3	3	1	2	12	15
X14	36	54	42	30	36	18	18	24	18	15	9	18	42	60
X15) X16)	6	12	15	6	2	6	9	5	6	21	1	21	18	24
X17	3	12	4	2	3		3	2		1	1	4	6	12
X18		15			1							2	3	1

Spring Gaugings, Upper Purau Valley, June 1987 to July 1988

Flows given in litres/minute

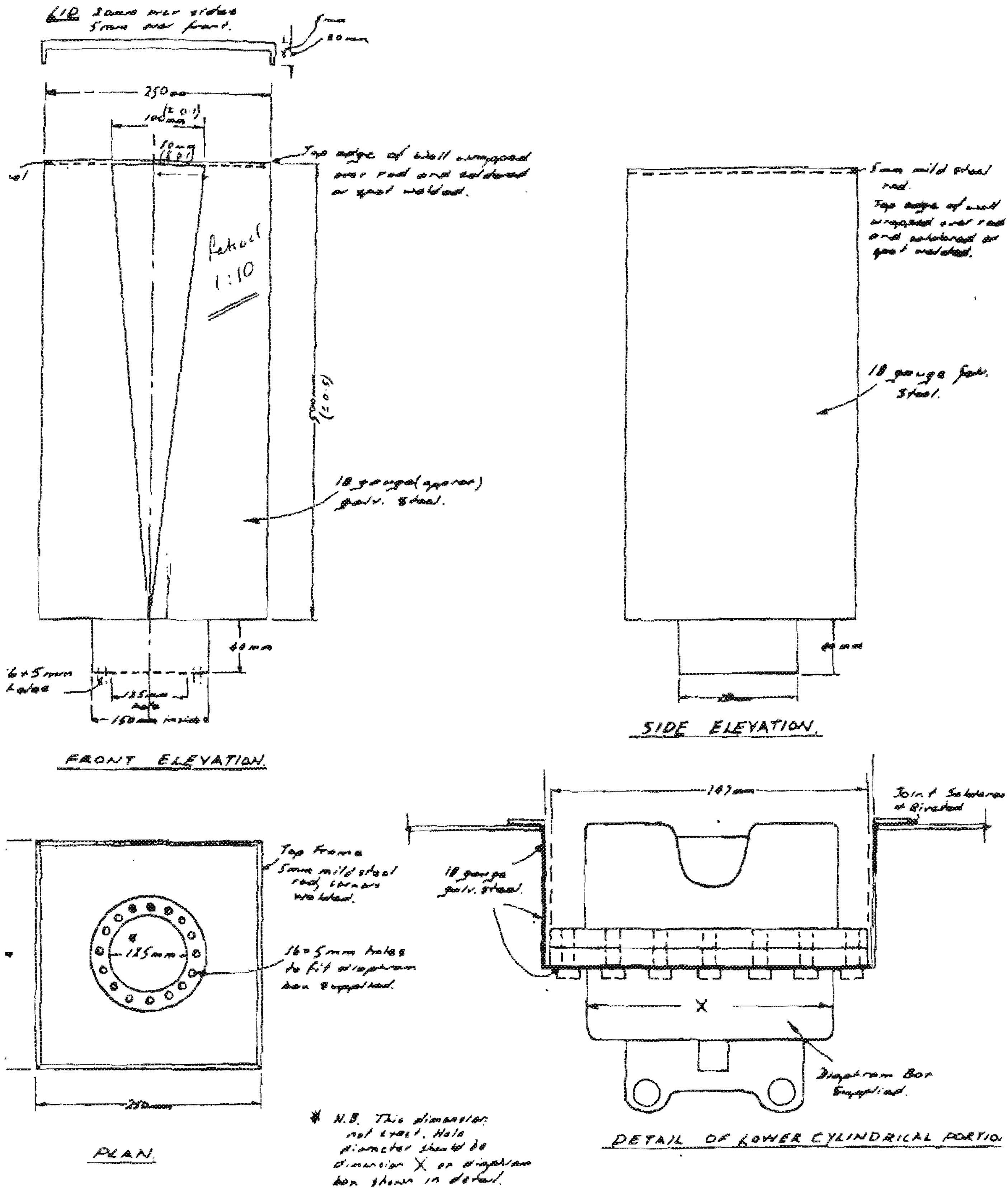
Flows measured by measuring the time taken to fill a known volume (eg a calibrated bucket).

Spring Number	12/6/87	24/6/87	29/6/87	3/7/87	17/7/87	21/7/87	30/7/87	31/7/87	18/8/87	20/8/87	8/9/87	10/9/87
1		17				6		12	2		4	
2		84				96		49	18		30	
3		60				108		67	18		24	
4		8				36		42	24		24	
5		300				708		450	101		132	
6	18		120		175		76			24		43
7	25		210		289		150			42		60
8	1		12		24		6			2		3
9	33		60		194		24			42		76
10	31		300		407		108			48		93
11	4		36		86		36			2		12
12	2		24		54		6			1		4
13				420		360		235	88		84	
14				36		48		40	24		24	
15				6		30		30	12		15	
16				30		18		6	2		4	
17				30		30		18	12		12	
18												
19				96		100		72	30		30	
20				96		190		156	30		42	
21				12		30		30	6		4	
22				2		6		6	2		4	
23				18		60		36	12		6	
24				12		30		18	6		2	
25				12		36		20	12		12	

Spring Number	25/9/87	19/10/87	29/10/87	26/11/87	17/12/87	18/1/87	22/2/88	15/3/88	31/3/88	18/4/88	5/5/88	30/5/88	28/6/88	26/7/88
1	3	18	6	3	1									
2	27	90	39	9									1	
3	13	33	24	3									2	
4	18	18	15	12	9	6	6	6	6	5	3	3	6	
5	185	348	150	84	60	24	18	15	15	12	9	12	180	
6	24	84	36	18	12	6	6	12	9	12	5	12	72	72
7	39	96	84	33	24	12	12	15	6	9	6	24	120	132
8	2	4	2	1			3						3	5
9	33	198	48	54	36	12	18	18	15	15	6	21	72	84
10	102	259	72	36	48	18	36	36	18	15	15	39	180	116
11	4	42		3										
12	3	24												
13	62	204	90		45	12	12	18	18	11	12	48	180	
14	18	18	18		12	12	3	6	3	6	6	3	18	
15	12	12	12		6	2		2					15	
16	3	18	3		3								8	
17	9	18	12		6	2							9	
18														
19	24	22	24		12	9	3	6	6	6	4	5	6	
20	24	24	21		6	12	12	6	6	6	4	3	6	
21	4	2	1											
22		2	1											
23	6	3	3											
24	3	3	3		1		1	1		1	1	1	1	
25	9	6	6		6	6	5	6	3	6	4	4	6	15

Diamond Harbour Spring Gaugings, June 1987 to July 1988

Flows given in litres/minute.



Mini V-notch weir specifications.